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Colorado State Univ., Fort Collins

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Robert S. Kerr Environmental Research Lab.
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EVALUATING FURROW IRRIGATION SYSTEMS FOR REGIONAL WATER QUALITY PLANNING

by

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16. ABSTRACT

Field evaluations of furrow irrigation practices at three Colorado locations were made during the 1979 irrigation season to develop a comprehensive data base. From these data, alternative field evaluation procedures were investigated as to the relationships between cost and accuracy. A simulation model based on traditional volume balance concepts was programmed and calibrated with the data base in order to evaluate if the relationships among furrow irrigation variables could be identified enroute to a general analysis of the effectiveness of improved practices on irrigation efficiency Analysis of spatial and temporal field variabilities indicate large errors in estimating the irrigation efficiency of a furrow irrigation system unless field testing is comprehensive. Testing needs to include the first water application each season and at least three subsequent irrigations to yield representative results. Further, at least six individual furrows across the field should be studied.

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FOREWORD

The enactment of the Clean Water Act of 1977 and the subsequent implementation of the Rural Clean Water Program emphasized the need for the development of improved technologies and strategies for controlling pollutants originating from agricultural and nonpoint sources. The management of irrigation return flows has been an important part of this laboratory's research on the occurrence, nature, movement, fate, impact and control of environmental contaminants.

This report describes a research effort to develop a reliable procedure for evaluating and predicting the effectiveness of improved practices on irrigation efficiency. An understanding of the effects of irrigation practice on the quality and quantity of irrigation return flows in a prerequisite for developing "Best Management Practices" for reducing water quality degradation. Information contained in this report should aid environmental planners as they design and implement pollution control strategies for irrigated agriculture.

Clinton W. Hall

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Director
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Research Laboratory

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ABSTRACT

Field evaluations of furrow irrigation practices at three Colorado locations were made during the 1979 irrigation season to develop a comprehensive data base. From these data, alternative field evaluation procedures were investigated as to the relationships between cost and accuracy. A simulation model based on traditional volume balance concepts was programmed and calibrated with the data base in order to evaluate if the relationships among furrow irrigation variables could be identified enroute to a general analysis of the effectiveness of improved practices on irrigation efficiency.

Analysis of spatial and temporal field variabilities indicate large errors in estimating the irrigation efficiency of a furrow irrigation system unless field testing is comprehensive. Testing needs to include the first water application each season and at least three subsequent irrigations to yield representative results. Further, at least six individual furrows across the field should be studied.

Extensive analysis of parameter interdependence indicated that temporal changes in field conditions must be simulated in order to produce an effective model of a furrow irrigation system. The assessment of changes in irrigation practices can be made from such models and are therefore important tools in establishing the cost-effectiveness of these improvements.

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ACKNOWLEDGEMENTS

This report represents a summary of three individual efforts made as part of the project under our direction by three Colorado State University graduate students, Mr. Ronald L. Elliott, Mr. Martin E. Neff, and Mr. Charles W. Binder. Their individual works will be referenced extensively herein and further presentations in the technical literature will bear their names as appropriate. For this writing, however, we wish to extend our sincere appreciation for their leadership during field data collection and subsequent reduction of that data, their careful attention to detail, and their willingness to work long, hard hours to ensure the success of this project.

As with any research effort of this size, there are also numerous support staff who contribute to the success or failure of the work. Some of these include Ms. Mary Lindburg and Ms. CeCe Cupparo who managed the typing of theses, reports, and papers, and Mrs. Betsy Zakely who maintained project records and coordinated the expenditure of the funds. We wish also to thank the three farmers who allowed the furrow evaluations to proceed on their lands. We were assisted during the project by our colleague, Dr. David Karmeli, and his efforts are also recognized.

Finally, we wish to acknowledge the support of the U.S. Environmental Protection Agency as represented by Mr. Alvin L. Wood, the Project Officer.

SECTION I

INTRODUCTION

BACKGROUND

The preparation of regional water quality management policies under Section 208 of PL 92-500 is guided by the requirement that states submit plans which "shall include . . . (1) a process to identify . . . agriculturally related nonpoint sources of pollution . . . and (2) a process to set forth procedures and methods . . . to control to the extent feasible such sources" (Law and Hornsby, 1977). The water quality degradation stemming from irrigated agriculture can be traced directly to the return flows. The volume and time distribution of these return flows are a function of irrigation efficiency.

The "208 Planners" should be able to segregate water pollutants attributable to urban, industrial, and irrigated agricultural sources from input-output data published regularly. The components of the irrigated agricultural component may be divided into a conveyance waste (seepage and spillage) problem and what might be termed as the "on-farm" problem. These planners will be very fortunate if the irrigation problem can be identified in respect to these two segments from existing data. Thus, there is necessity in collecting at least some field information. Such efforts so far as the conveyance system is concerned, are relatively simple but not inexpensive. The on-farm evaluations, however, are neither simple nor inexpensive because of the enormous variety of farming practices and physical conditions even within comparatively small areas.

Improved irrigation practices have become increasingly important due not only to pollution control needs, but also to water and energy conservation, and the need for increased food and fiber production. Irrigated agriculture accounts for approximately 34 percent of the water withdrawal in the United States and 83 percent of the water consumption (Murray and Reeves, 1977). The total on-farm energy use in the United States as estimated for 1977 was about 3 percent of the nation's total energy use (ERS, 1977). Irrigated agriculture's role in increased food and fiber production is emphasized by noting that irrigated agriculture accounts for 10 percent of the total agricultural land use while comprising 25 percent of the total crop production (FWPCA, 1968). Pollution control considerations are important due to irrigated agriculture contributing salts, nutrients, sediments, and pesticides to many rivers throughout the world.

Sixty-eight percent of the total irrigated acreage in the United States is surface irrigated (Irrigation Journal, 1979). Furrow irrigation, which comprises a major portion of this acreage is characterized by running water down small channels or furrows between crop rows. Properly designed and managed furrow irrigation systems can result in high crop production levels while conserving water and energy resources. However, inherent system limitations coupled with poor management practices can and often do result in large deep percolation and tailwater runoff volumes.

The factors controlling furrow irrigation performance are complex but can be classified in two main areas. The first area is broadly classified as physical characteristics of the irrigation system. These include soil intake properties, furrow slope, shape, and length, and frequency of water applications to note only a few. Furrow irrigation performance is also a function of nontechnical factors such as socioeconomic conditions, institutional and legal constraints. Each irrigated area has its own unique combination of water delivery mechanisms operated by an array of administrative policies which can be traced to the historical decisions by the irrigators themselves and a host of governmental entities.

Researchers dealing with the irrigation return flow system have been concerned with the severe problem of collecting data on a large enough scale to ensure an adequate description of these large-scale irrigated systems. It appears that the existing manpower base of the planning consultants and agencies and the funding committed to water quality planning are likely to be insufficient to facilitate studies of the same detail as those engaged in by research professionals. Consequently, the investigation tools applicable at the planning level must be much simpler to accommodate the kinds of data that can be realistically collected. The work reported herein is intended to provide such a simplified, usable computational aid and to concisely describe the procedures and limitations of the suggested approach.

OBJECTIVES AND WORK PLAN

If the individual factors contributing to an irrigation return flow problem cannot be effectively defined, then it should be obvious that the "Best Management Practices" for reducing the impact cannot be determined. The principal objective of this proposed research was to amend this problem at least partially by developing and verifying a field evaluation procedure for planners attempting to delineate the on-farm factors affecting irrigation return flows. Once defined, understanding these factors can be utilized to evaluate the measures that might be employed to improve on-farm irrigation efficiency and their effectiveness. In order to accomplish the principal objective, the following intermediate tasks were delineated:

1. Utilizing existing field data and relationships describing furrow irrigation system performance, a model was to be formulated which requires only furrow inflow rate, furrow length, advance rates, and the length of time water is applied to the fields to estimate field and application efficiencies. It was assumed that the soil moisture depletion at the time of irrigation could be determined gravimetrically;

2. The predictions of the simplified model were then to be tested against available field data and the prediction of the more complete

and correct models in order to define the limits and reliability of the simple model;

3. The simple model would be used to predict the increased efficiency that could be expected if the irrigator had better information as to the amount of water to apply, if furrow inflows and length were adjusted, or if cut-back or reuse systems were constructed;

4. Field data were not available to verify the model predictions under modified conditions. Consequently, it was necessary to collect some field data in which the model is initially calibrated, predictions of the efficiencies resulting from changes in irrigation practices are made; and, these changes are imposed temporarily on the real system so that the actual effects can be compared to the predictions; and

5. For the conditions where the simplified model can be applied with the same accuracy as other estimates in a planning process (say 25 to 30 percent), the field and analytical procedures were set forth in a planning manual. The manual will include easy to use charts and tables derived by synthesizing model predictions over the entire range of model parameters.

SCOPE OF STUDY

A review of the analytical basis for furrow irrigation evaluation and improvement in a later section will demonstrate the substantial emphasis given to theoretical description. Data have been collected to verify these models, but a careful review of this information shows nearly all of it to be incomplete in one or more measurements that are essential if a system planning framework is to be evaluated. The scope of this project, therefore, included a major effort to collect and organize sets of furrow test data that could be used to compare, refine, or develop methods for defining furrow irrigation performance. A similar effort was also under way by the Soil Conservation Service, USDA, as part of their efforts to revise Chapter 5, "Furrow Irrigation," of their National Engineering Handbook. These data were not available to this project so the data sets developed come from studies conducted at Colorado State University during the 1977 and 1979 irrigation seasons.

Furrow evaluation data were collected at the six Colorado farms located in Figure 1. Tables 1 and 2 provide general information concerning each of these sites. For the three farms studied in 1979, more specific soil texture data are presented in Tables 13, 14 and 15 in Appendix A. On each farm, a group of furrows consisting of three test furrows and the accompanying "guard" furrows were evaluated. In most but not all cases, data were obtained from each of the three test furrows within a group. A summary of the basic data for the farms studied in both 1977 and 1979 are included in Appendix A as Tables 16 through 19.

All of the data were organized into a report entitled, "Furrow Irrigation Field Evaluation Data," by Ronald Elliott (1980). The report is an internal Colorado State University document available upon request from the second writer.

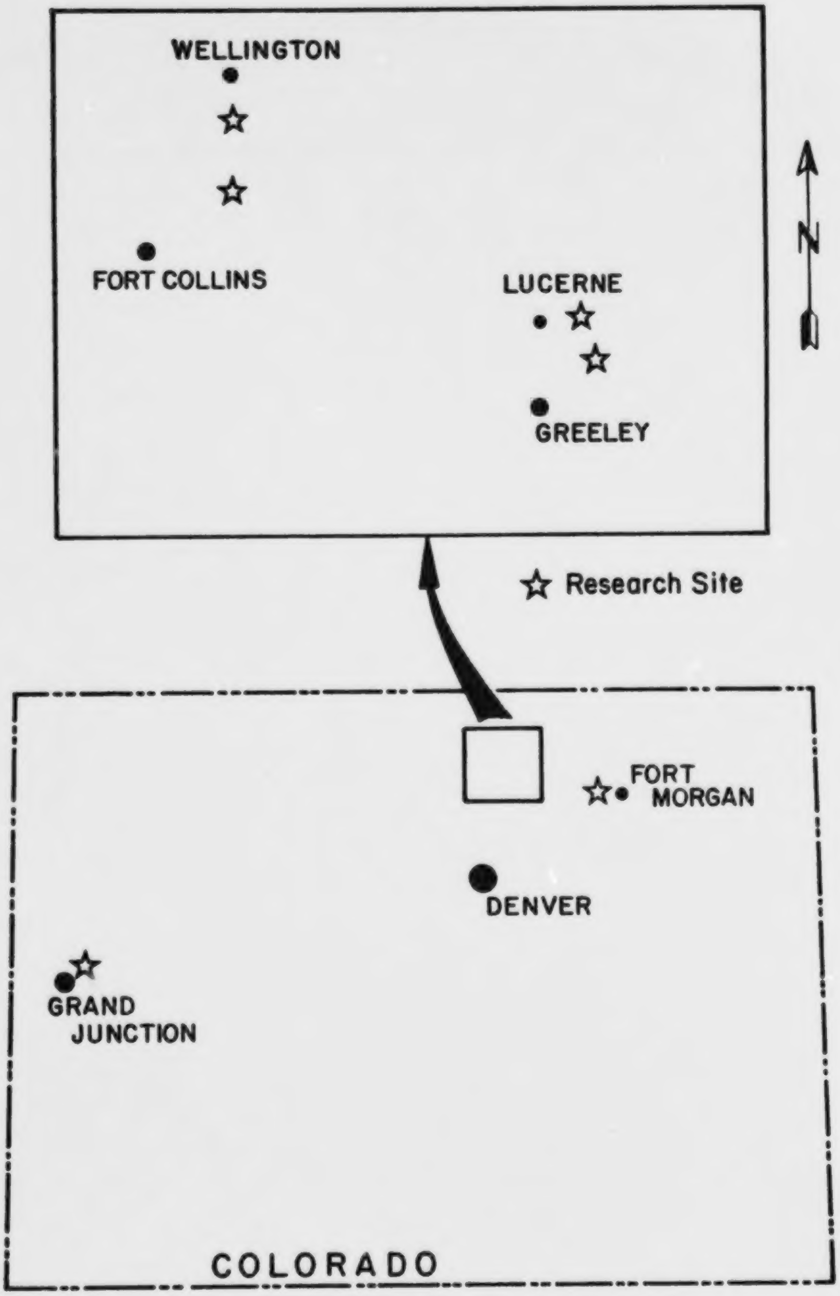
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Figure 1. Locations of the six research sites (from Elliott, 1980).

TABLE 1. GENERAL INFORMATION ON FIELD RESEARCH SITES (FROM ELLIOTT, 1980).

Name of Farm	Approximate Location	Soil Type	Year of Study	Crop	No. of Furrow Groups Studied
Kenneth Benson	2 mi. east of Lucerne, CO	Clay Loam	1979 1977	Corn Corn	2 1
CSU Horticulture Farm	3 mi. northeast of Fort Collins, CO	Clay Loam	1977	Cucumbers	1
Kenneth Matchett	3 mi. northeast of Grand Junction, CO	Loam to Clay Loam	1979	Corn	4
Northern Colorado Research and Demonstration Center (NCRDC)	2 1/2 mi. northeast of Greeley, CO	Sandy Clay Loam	1977	Corn, Beans	2
Carl Printz	1 1/2 mi. west of Fort Morgan, CO	Loamy Sand	1979	Corn	2
R. L. Stieben	2 mi. south of Wellington, CO	Clay Loam	1978	Sugar beets	1

TABLE 2. FURROW LENGTHS, SPACINGS, AND SLOPES FOR THE RESFARCH SITES (FROM ELLIOTT, 1980).

Farm	Year	Group Number	Furrow Length (m)	Furrow Spacing (m)	Furrow Slope (m/m)
Benson	1979	1	625	1.524	.0044
		2	625	1.524	.0044
	1977	1	625	1.542	.0045
Horticulture	1977	1	175	1.118	.0036
Matchett	1979	1	375	0.762[1]	.0088
		2	400	0.762[1]	.0101
		3	425	0.762[2]	.0095
		4	450	0.762[2]	.0092
NCRDC	1977	1	175	1.542	.0038
		2	175	1.118	.0043
Printz	1979	1	350[3]	1.524	.0023
		2	350	1.524	.0025
Stieben	1978	1	350	1.118	.0098

[1] Spacing was 1.524 m for irrigation 3.

[2] Spacing was 1.524 m for irrigation 4.

[3] Length was 325 m for irrigation 3.

After the data had been reduced to computer coded files, two extensive analyses were made to interpret the data. The first entitled, "Cost-Effectiveness of Furrow Irrigation Evaluation Procedures" by Martin E. Neff is an unpublished M.S. thesis, Department of Agricultural and Chemical Engineering, Colorado State University. The second entitled, "Improving Furrow Irrigation Performance through Management Decisions" by Charles W. Binder, Department of Civil Engineering, Colorado State University. The sections that follow include the results of these two theses.

SECTION II

CONCLUSIONS

FIELD EVALUATION PROCEDURES

Equations for subsurface infiltrated volumes were obtained by separate integration of terms in the volume balance equation. The incomplete Beta function appeared in the solution as an infinite series. The first several terms of the series were used to approximate the incomplete Beta function solution and made computation of any infiltrated volume a fairly simple process.

Data from 18 furrows representing 6 furrows from each of three sites were analyzed for five irrigations. The performance of each furrow was determined using a detailed evaluation (Procedure 4) as described in Appendix B.

Three alternate field evaluation procedures were devised that were less expensive and easier to apply than Procedure 4. These alternates were compared with the measured performance (Procedure 4) furrow-by-furrow, irrigation-by-irrigation, and site-by-site in a systematic manner. Average absolute fractional deviations were obtained from these analyses.

Costs applicable to all procedures in terms of labor and equipment were determined for the different possible levels of evaluation (number of furrows evaluated) and compared to the deviations found for each procedure.

Based upon the approach described above, the analysis led to the following conclusions.

1. The volume balance equations allow an easy means of computing the temporal distribution of infiltration.

2. Several simplifications were found that aided the development of the alternate procedures.

    a. Use of the parabolic assumption for furrow cross-sectional area using depth and top width readings at a station near the head of the furrow appears to be a valid simplification. Variations in surface storage volumes computed using these cross-sectional areas appeared to have little influence on application efficiencies but could have a definite influence on the deviation of the tailwater ratio and deep percolation ratio depending on the magnitude of these losses.

b. The viability of simplifications made by estimating the soil moisture deficit by the "feel method" depends a great deal on the experience of the technician. A period of calibration may need to be implemented before using the "feel method" soil moisture deficits (SMD) by taking gravimetric moisture samples to compare with the results of the "feel" of a soil. This would allow even the most inexperienced individual to become more adept at estimating SMD by this method.

c. The flow rate estimation performed for Procedure 1 is largely a function of experience. Flow rates for a portion of an irrigation on the Matchett farm could be determined in this fashion, and the estimated flow rates were quite close to those measured. Values of flow used in the analysis of Procedure 1 may possibly deviate more than would be expected, even for an experienced individual estimating discharge rates.

d. The estimation of the c' value using "book values" results in some error. Values of c' equal to zero will generally underestimate the infiltrated volume, thus increasing the tailwater ratio while decreasing the deep percolation ratio. Values of c' selected for this evaluation were conservative. The exact contribution to errors in predicted efficiencies caused by a poor estimate of the c value becomes a problem of separating the contributions of the infiltration constants to the infiltrated volumes.

3. Overall, Procedure 3 is the most accurate when at least three irrigations are evaluated. The use of inflow and outflow information in any evaluation (rather than estimates) would be expected to enhance the accuracy of any alternate procedure.

4. Overall, the most cost-effective procedure is also Procedure 3. A good portion of the cost of applying Procedure 3 is due to the time needed to compute the infiltration parameters and performance from the actual flume data. If computer services are available, this time can be substantially reduced with a corresponding reduction in hourly costs.

MODEL PREDICTION

An empirically based simulation model (Program FURSIM) has been developed in an effort to provide a simple tool for assisting system operators in making the proper furrow irrigation management decisions. The model predicts furrow irrigation performance as a function of the principal decision variables: furrow discharge, time of cutoff, soil moisture deficit, and number of previous irrigations. The system state variables are described by a series of functions determined by a regression analysis. The primary state variable functions include the advance coefficient functions and the basic intake rate function. The primary mathematical elements of the model include: (a) the furrow cross-sectional flow area and the furrow wetted perimeter are represented as a power function of flow depth; (b) Manning's roughness factor is used to describe furrow roughness; (c) a power function is used to characterize the rate of advance down the furrow; (d) the modified Kostiakov equation is used for describing infiltration with the basic equation being extended to incorporate wetted perimeter and seasonal variation effects; (e) the subsurface water distribution is described by an integration technique as opposed to an average subsurface shape factor; (f) the volume balance approach is used for determining infiltration coefficients based on the advance characteristics; and (g) the irrigation performance is characterized by four parameters--application efficiency, requirement efficiency, runoff ratio, and deep percolation ratio.

1. The model has been verified using field data collected at three locations over a period of three years. The model has been extended to operate in a production mode. Performance prediction curves have been developed based on program FURSIM. The curves can be utilized as a tool for making furrow irrigation management decisions. Examples have been given to display the utility of the prediction curves as part of a management improvement program.

2. The data collection procedure used as part of this study is basically sufficient for measuring the state variable behavior in a furrow irrigation system. State variable functions have been developed enabling system performance to be predicted as a function of decision variable modification. However, a review of the collected data and the model development process reveals three areas where the data collection does not adequately measure the state variable behavior. Manning's n cannot accurately be determined with the collected data due to difficulty in measuring the furrow discharge, flow depth, and hydraulic radius along the furrow. However, this study and others previous have shown that an approximate estimate of Manning's n may be sufficient.

3. The model development process has disclosed, in accordance with what many others have previously shown, the necessity of quantifying the balance during the recession phase. This is especially true when the surface storage is not relatively small compared to the total volume of water applied. The recession times were observed during the data collection; however, ambiguities in the data and utilization of the data have led the authors to believe that the recession phase should be quantified on a macro-scale basis. The total volume of runoff during the recession phase should be measured. This enables development of the system f-function. The total volume of infiltration during recession can then be determined; however, the exact distribution of this volume is not known.

4. The lateral movement of the infiltrated water could not be quantified based on the collected data. The significance of not accurately describing the lateral movement is demonstrated when determining the volume of water required in the root zone. The assumption that an effective root zone extends throughout the furrow spacing results in over-estimating the requirement. However, a study to quantify the lateral movement phenomena would be quite costly and from an implementation viewpoint is probably not practical.

5. The study has shown that the state variables describing a furrow irrigation system are multi-dependent. The state variable functions are dependent upon both decision variables and state variables. The variables and system properties that influence state variable quantification include soil type, furrow geometry, number of previous irrigations, soil moisture deficit, surface soil moisture content, furrow discharge, and wetted perimeter. However, for modeling purposes, it has been found that many dependents must be neglected due to the inability to mathematically describe the functional relationships. Consequently, many known dependents have been omitted from the state variable function arguments.

6. A method of empirically modeling furrow irrigation at a limited implementation level has been developed. The limitation is primarily due to the necessary individual site calibration and the level of sophistication of the model output. The model verification has shown that the basic functional relationships incorporated into the model apply to the system. The individual site calibration has been found to be accurate to within an acceptable range accounting for system characteristics, variability and measurement accuracy. The spatial variability in soil hydraulic properties is a major concern at the model implementation level.

7. The direct model output and the performance prediction curves based on the model provides an estimate of system performance as a function of management decisions. However, the inability to incorporate a simple correction factor for the number of previous irrigations into the output has resulted in restricted utilization of the model. A simple correction factor could not be developed due to the model's inherent accounting for irrigation number.

SECTION III

RECOMMENDATIONS

The fundamental relationships describing the state variables need to be confirmed. Further study regarding the f-function (the fraction of surface storage at the time of cutoff that infiltrates) would be beneficial due to the possibility of deleting the need for knowing the time characteristics of recession. The function arguments could possibly include furrow discharge, wetted perimeter, and basic intake rate. However, from a modeling viewpoint, it would be advantageous to relate f solely to soil type.

Further study regarding the surface soil moisture (θ) function is necessary. The present form of the function relates θ to the total soil moisture deficit with a moderately high coefficient of determination (0.58-0.68). However, the surface soil moisture content is highly dependent upon rainfall, which should be incorporated into the function.

The existing form of the performance prediction curves should be extended in two areas. A simple correction factor to account for the number of previous irrigations needs to be determined and incorporated into the curves. The curves also need to be extended to determine the performance parameters directly instead of using equations.

An acceptable measure of the subsurface shape factor or infiltrated uniformity should be incorporated into the model. The x_D value determined by Program FURSIM does give an indication of the uniformity. However, even though the distance $x_D \leq x \leq L$ may not have received the requirement, a portion of the root zone was filled with water. Consequently, the accepted uniformity measure should be based on the infiltrated volume contributing to crop consumptive use in terms of crop yield.

The concept of maximum nonerosive discharge should be incorporated into the model. The need exists for determining the economic threshold of furrow erosion before this system constraint can be practically applied. Inspection of the data at all three study sites reveals that the existing furrow discharge was greater than the maximum discharge determined by the Hamad and Stringham (1978) technique. However, from the irrigator's point of view, the existing furrow discharge was acceptable.

The model should be extended to include an option for simulating cutback, runoff recovery, and cutback/runoff recovery hybrid systems. Field data should be collected from cutback systems to ensure accurate characterization of the state variable functions. The key system characteristic that must be properly described is the time distribution of runoff.

SECTION IV

EXPERIMENTAL AND ANALYTICAL APPROACH

THEORETICAL BASIS

Water flow over a soil surface is both spatially varied and unsteady. The discharge at a specific location changes with time due to the time dependent intake behavior of the soil. At the advancing end of the water body, particularly, depth also changes with time and space. In order to characterize the flow, expressions must be developed to describe both continuity of mass and conservation of momentum or energy. A model utilizing these equations is generally referred to as hydrodynamic, but research is just now adapting this analysis to furrow irrigation systems. Two simplifications of the hydrodynamic analysis are available for border irrigation but not furrow systems. These models either neglect any effects of inertia or assume uniform flow.

The next level of mathematical sophistication is to consider only the conservation of mass. This technique is called the volume balance or kinematic approach and has received the most attention in the literature. It is the only mathematical approach that has been effectively applied to furrow irrigated systems on a field scale, and it represents the theoretical basis of all field evaluation procedures. A complete description of the volume balance approach to furrow evaluations must extend from the integration of the mass conservation equation to an expression of irrigation efficiency. Such descriptions are found in the recent work of Gerards (1978), Ley (1978), Evans et al. (1978) and several others. It is worthwhile to repeat this important mathematical framework here in order to complement the discussion of the experimental and analytical approaches.

Volume Balance

Most volume balance studies consider the condition where a steady flow is introduced onto a relatively dry permeable land surface having a uniform shape in the direction of flow and no lateral slope. Irrigation proceeds through four basic phases:

1. Advance -- the inflowing stream moves from the field inlet to the end of the field;

2. Ponding -- after flow reaches the end of the field and before it is shut off, water elevations stabilize if flow is leaving the field (tailwater) or builds up to a level profile if the end is diked;

3. **Depletion** -- following the shut off of inflow discharge, the ponded profile infiltrates and recedes until the soil at the upper end of the field is completely drained; and then

4. **Recession** -- water drains from the field toward the lower end or infiltrates into the soil eventually leaving the field surface void of a free water surface.

Depending on the field slope condition for the lower end of the field, time of cutoff relative to time of advance, and other factors not all of the four phases will be present. For furrow irrigated systems, advance is the major interest and ponding, depletion, and recession can often be neglected.

Consider the profile view through the center line of a furrow shown in Figure 2. At the time, t, the flow has advanced to the point x creating both a surface water profile and a subsurface water profile. The volume of water stored above ground is:

$$\forall_y(t) = \int_0^x A(s,t)ds \qquad (1)$$

where,

$\forall_y(t)$ = volume of surface storage as a function of time;

$A(s,t)$ = cross-sectional flow area in the furrow as a function of time and distance; and

s = integration parameter for distance, $0 \leq s \leq x$.

Similarly, the volume of water stored in the soil is:

$$\forall_z(t) = W \int_0^x z(s,t)ds \qquad (2)$$

in which,

$\forall_z(t)$ = volume of subsurface storage as a function of time;

W = furrow spacing; and

$z(s,t)$ = infiltrated depth per unit furrow width, also as a function of distance and time.

If the inflow to the furrow (Q_o) is assumed steady as it must be for the volume balance approach, then Equations 1 and 2 can be combined to yield the basic volume balance model:

$$Q_o t = \int_0^x A(s,t)ds + W \int_0^x z(s,t)ds \qquad (3)$$

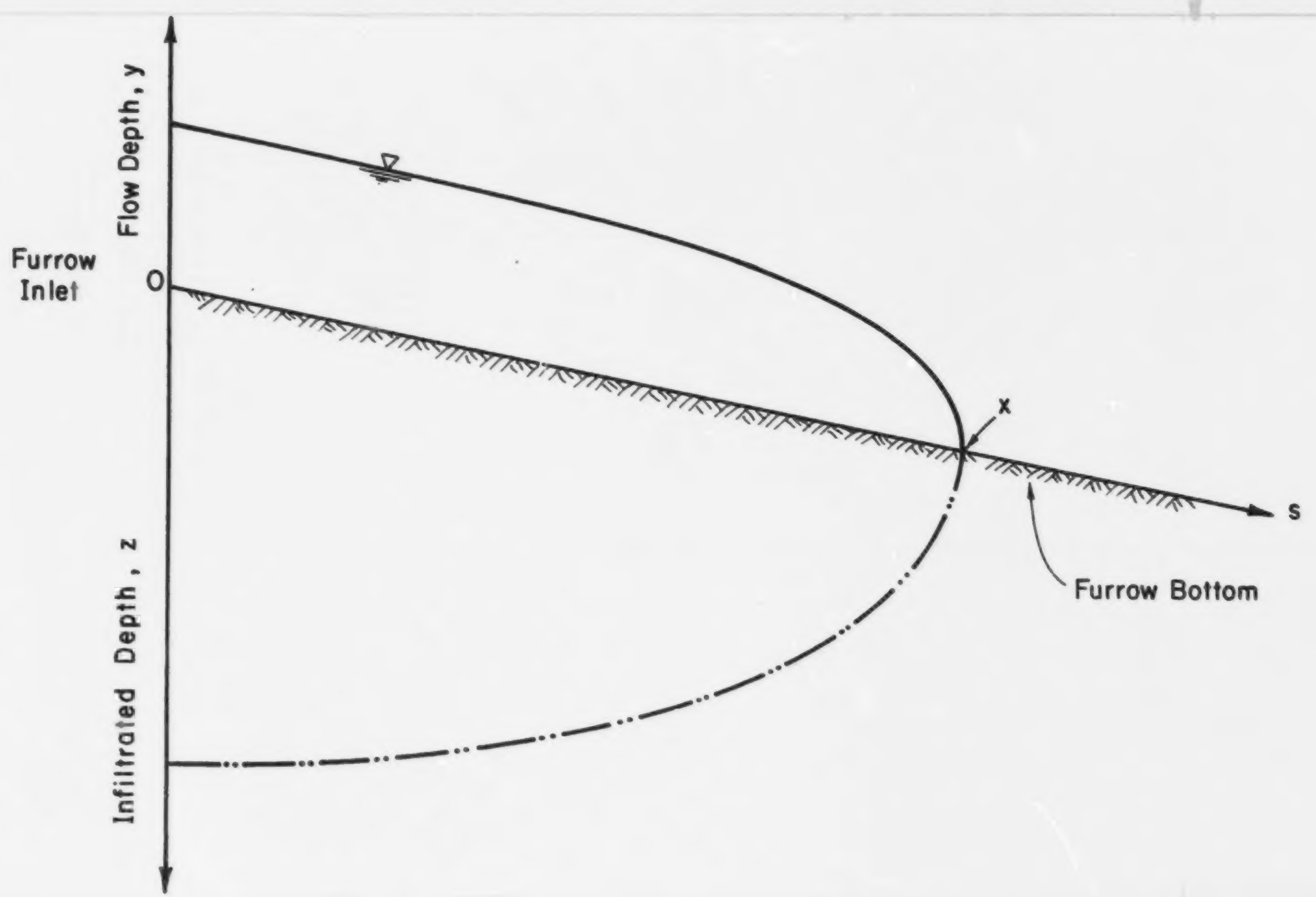
Flow Depth, y
Furrow Inlet
O
x
s
Furrow Bottom
Infiltrated Depth, z

Figure 2. Cross-sectional view showing water surface and infiltrated depth profiles through a furrow centerline.

The two terms on the right-hand side of Equation 3 are coupled and technically require a second equation (momentum or energy) to be jointly solved. Since the momentum or energy relationship is ignored, two assumptions must be made to provide solutions to Equation 3. The first is that the first term on the right-hand side can be replaced by the following:

$$\int_{o}^{x} A(s,t)ds = \sigma_y A_o x \tag{4}$$

where,

A_o = cross-sectional flow area at the furrow inlet; and

σ_y = shape factor describing the relationship between the inlet area, A_o, and the average area, $\bar{A}$, of the flow.

The second assumption is that the intake characteristics of the soil can be described by a function of known mathematical form and be dependent on "intake opportunity" time, i.e. related to the time water is actually covering the surface. The effects of water depth are neglected initially but will be partially included later in the analysis. These assumptions allow the second term on the right-hand side of Equation 3 to be written:

$$W \int_{o}^{x} z(t-t_s)ds = \sigma_m z_m x \cdot W \tag{5}$$

in which,

z_m = infiltrated depth at the field inlet per unit furrow spacing;

σ_m = subsurface shape factor relating the inlet infiltrated depth, z_m, to the average infiltrated depth, $\bar{z}$; and

t_s = time of advance to s.

The results of making the modifications to Equation 3 noted in Equations 4 and 5 were first discussed by Lewis and Milne (1938), yet analytical solutions did not appear in the literature until 25 years later when Farrell (1963) and then Philip and Farrell (1964) applied Laplace transforms in conjunction with several intake functions. Unfortunately, the Philip and Farrell solutions were substantially more elegant than practical and many subsequent efforts have been made to develop usable mathematical approaches.

For the reader interested in the formulation of the numerous volume balance approaches described in the literature, references such as Hart et al. (1968) are suggested. These works note that in defining the relationships between the infiltration function, z(s,t), the advance function, x(t), and the surface profile shape, $\bar{A}(t)$, any two may be given a particular mathematical form and the third can be solved from the volume balance equation. However, to assume the functional form of all three " . . . represents an overconditioning of the problem and consequently a violation of the volume balance . . ." (Hart et al., 1968). Yet, nearly all of the volume balance methodologies commonly used in conjunction with field studies make assumptions concerning all three factors and actually do fit field conditions very well. The logical question is why this is possible. The answer lies in the subtle fact that field studies are always concerned with evaluations over a relatively large time, say 4 to 48 hours. Many investigators such as Hart et al. (1968) show that for long periods of time, the true solutions to the volume balance model satisfy the conditions created by the assumptions.

In reviewing the volume balance literature with a view toward applications to field evaluations, several modifications and refinements have been added by students working under the direction of the writers (Gerards, 1978; Neff, 1981; Binder, 1981; and Elliott and Walker, 1980). The analysis that follows is based on the following three assumptions which repeat earlier comments.

1. Infiltration is expressed by either:

$$\frac{\partial z(s,t)}{\partial t} = a(t-t_s)^b \tag{6}$$

or,

$$\frac{\partial z(s,t)}{\partial t} = a(t-t_s)^b + c(t-t_s) \tag{7}$$

where a, b, and c are empirical constants;

2. Advance is related to time as follows

$$x = pt^r \tag{8}$$

where p and r are empirical constants; and

3. The cross-sectional flow area is constant for a given furrow inflow, or

$$\overline{A} = \text{constant} = \sigma_y A_o \tag{9}$$

where σ_y has a constant value of 0.77 based on field experience.

In addition, the planning level emphasis of this work suggests that unless the slope of the furrow is nearly level, or the furrow ends are diked, then the volume of surface storage after the time of cutoff can be considered negligible.

Furrow Irrigation Efficiencies

The performance of a furrow irrigation system can be described in several ways. For a water quality orientation, performance indicators should include the following parameters:

1. Application Efficiency, E_a:

$$E_a = \frac{\text{Depth or Volume of Water Stored in Root Zone}}{\text{Depth or Volume of Water Delivered to Field}} \times 100 \qquad (10)$$

2. Deep Percolation Ratio, DPR:

$$DPR = \frac{\text{Depth or Volume of Deep Percolation}}{\text{Depth or Volume of Water Delivered to Field}} \times 100 \qquad (11)$$

3. Field Tailwater Ratio, TWR:

$$TWR = \frac{\text{Depth or Volume of Field Tailwater}}{\text{Depth or Volume of Water Delivered to Field}} \times 100 \qquad (12)$$

Three general cases of furrow irrigation performance can be identified in relationship to Equations 10, 11 and 12. The first case, depicted in Figure 3 occurs when the least watered areas of the field receive exactly the root zone storage deficit. Figure 3 represents the subsurface water distribution over an imaginary furrow length, ℓ, and a unit furrow spacing, W. At the time of irrigation, the average soil moisture deficit is the root zone soil moisture holding capacity, D, times the actual field length, L. Thus, Equations 10 to 12 can be written in terms of the graphical subareas, A_1', A_2', and A_3', as:

$$E_a(CI) = \frac{A_1'}{A_1' + A_2' + A_3'} \times 100 \qquad (13)$$

$$DPR(CI) = \frac{A_2'}{A_1' + A_2' + A_3'} \times 100 \qquad (14)$$

and,

$$TWR(CI) = \frac{A_3'}{A_1' + A_2' + A_3'} \times 100 \qquad (15)$$

where the instruction (CI) refers to the "complete-irrigation."

The situation depicted by Figure 3 is generally the optimal or near optimal irrigating policy, but is seldom achieved due to uncertainty in defining the root zone soil moisture holding capacity, D, and the inability to precisely control the rate water moves over the field. A more typical situation is the case when more water is applied than is necessary over the entire

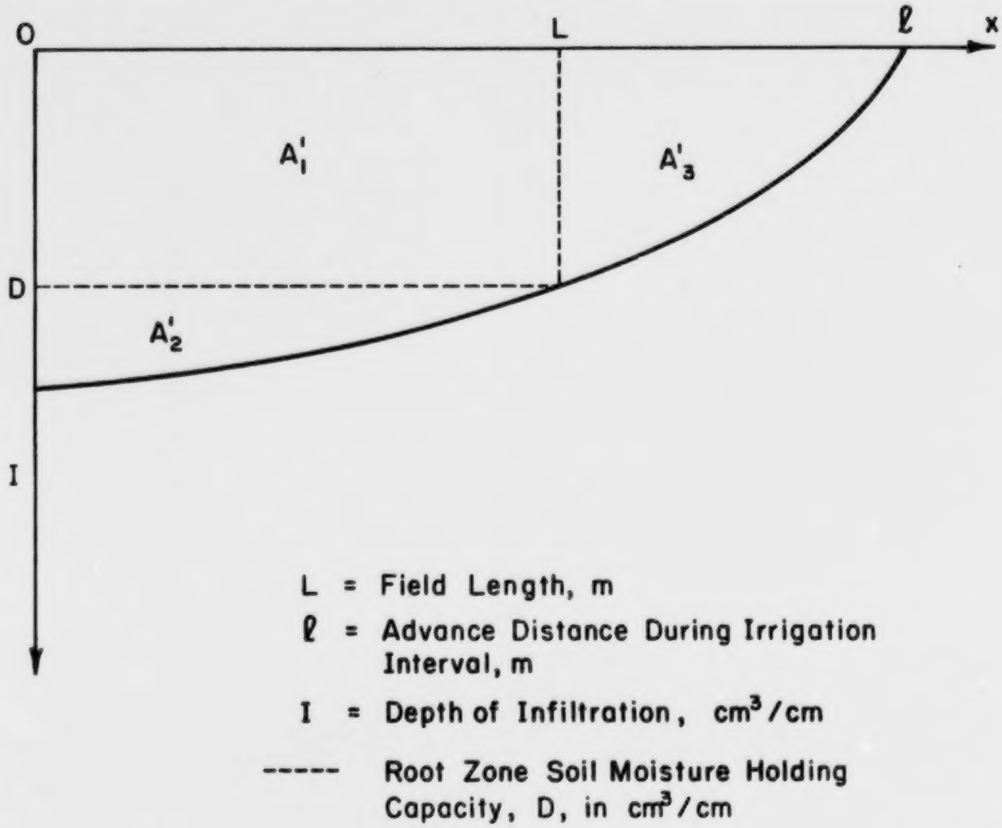
O
L
ℓ
x
A'_1
A'_3
D
A'_2
I
L = Field Length, m
ℓ = Advance Distance During Irrigation Interval, m
I = Depth of Infiltration, cm³/cm
----- Root Zone Soil Moisture Holding Capacity, D, in cm³/cm

Figure 3. Defnition sketch of furrow irrigation subsurface water distribution for the "complete irrigation" case.

field (over-irrigation, OI) as illustrated in Figure 4. Equations 13 to 15 apply to this case as well.

Occasionally not all of the root zone deficit is refilled and an under-irrigation (UI) condition prevails as shown in Figure 5. The root zone is refilled to a distance x_D with the resulting efficiency parameters defined as:

$$E_a(UI) = \frac{A_1' + A_5'}{A_1' + A_2' + A_3' + A_5'} \times 100 \qquad (16)$$

$$DPR(UI) = \frac{A_2'}{A_1' + A_2' + A_3' + A_5'} \times 100 \qquad (17)$$

and

$$TWR(UI) = \frac{A_3'}{A_1' + A_2' + A_3' + A_5'} \times 100 \qquad (18)$$

It can be noted that E_a + DPR + TWR = 100; therefore, these three indicators reflect collectively a mass balance of the water entering the furrow (again, assuming surface storage is negligible relative to subsurface storage).

A more analytic formulation of the preceding efficiency parameters can be realized by deriving a function for σ_m, the subsurface shape factor. Equation 2 written with the inclusion of Equation 6 integrated with respect to time and referenced over the length of advance if the furrow had been infinitely long yields:

$$\forall_z(t_\ell) = W \int_o^\ell \frac{a}{b+1} (t_\ell - t_s)^{b+1} ds \qquad (19)$$

where t_ℓ is the total irrigation time. Letting $a' = a/(b+1)$, $b' = b+1$, and $t = t_s/t_\ell$ allows Equation 19 to be transformed into the following equation:

$$\forall_z(t_\ell) = (a' t_\ell^{b'})(p t_\ell^{r})\, Wr \int_o^1 (1-t)^{b'} t^{r-1} dt \qquad (20)$$

Thus, the subsurface shape factor σ_m is equal to r times the integral which, as a matter of interest, is the Beta function. An approximation to the Beta function is given by Kiefer (1959):

$$\sigma_m = r \int_o^1 (1-t)^{b'} t^{r-1} dt = \frac{b' - b'r + r + 1}{(b'+1)(r+1)} \qquad (21)$$

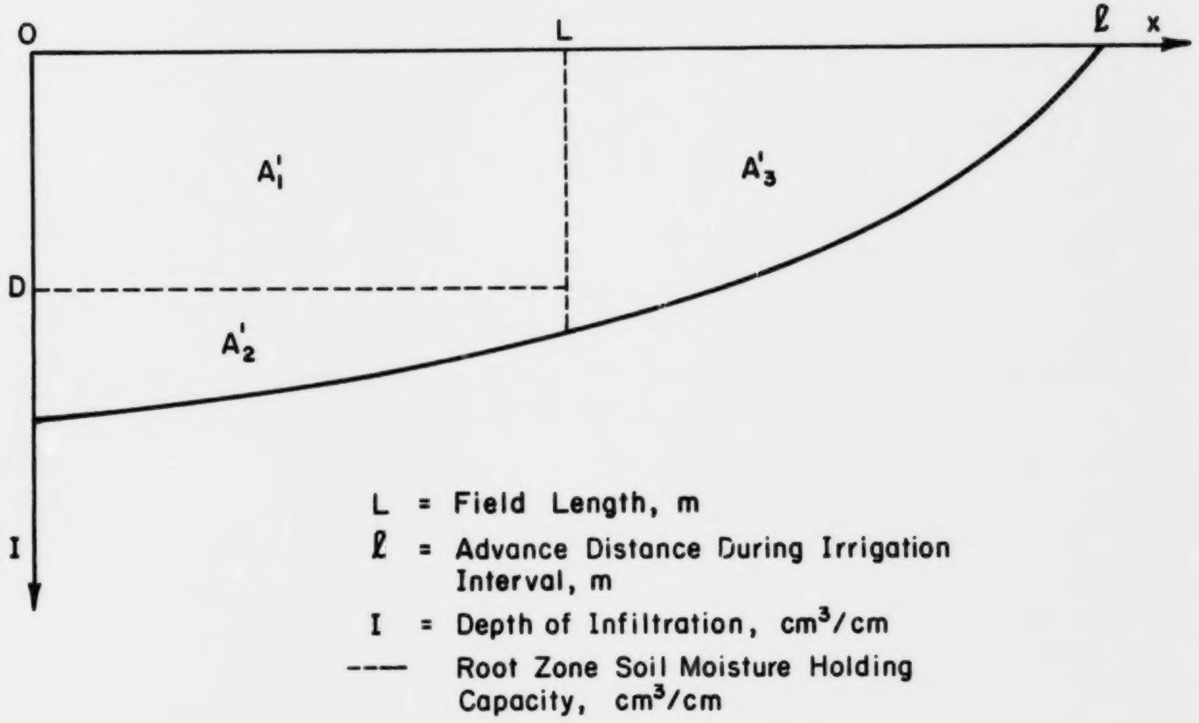
O
L
ℓ
x
A'1
A'3
D
A'2
I
L = Field Length, m
ℓ = Advance Distance During Irrigation Interval, m
I = Depth of Infiltration, cm³/cm
---- Root Zone Soil Moisture Holding Capacity, cm³/cm

Figure 4. Definition sketch of furrow irrigation subsurface water profile for the over-irrigation condition.

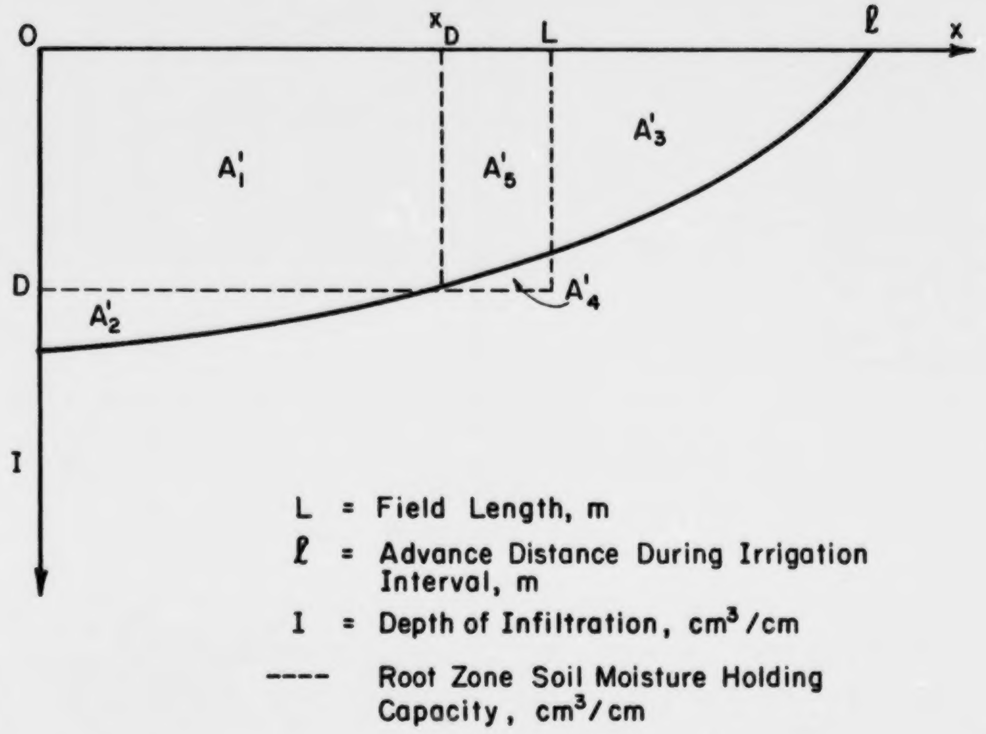
O
x_D
L
ℓ
x
A'_1
A'_5
A'_3
D
A'_4
A'_2
I
L = Field Length, m
ℓ = Advance Distance During Irrigation Interval, m
I = Depth of Infiltration, cm^3/cm
---- Root Zone Soil Moisture Holding Capacity, cm^3/cm

Figure 5. Definition sketch of furrow irrigation subsurface water distribution for the case where part of the field is under-irrigated.

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The variable $\forall_z(t_\ell)$ represents the total inflow to the furrow during the irrigation interval. However, for definition of the individual areas in Figures 3 to 5, the solution to Equation 20 must be made bv integrating over intermediate time ratios. For example, if the subsurface volume within the confines of the actual furrow itself is desired, the integration would be as follows:.

$$\forall_z(t_L) = a' t_\ell^{b'} p t_\ell^{r} \, W r \int_0^P (1-t)^{b'} t^{r-1} dt \qquad (22)$$

in which,

t_L = time for flow to advance the furrow length, L; and

$P = t_L/t_\ell$.

Gerards (1978) labeled the product of r and the partially integrated Beta function as the "incomplete Beta function." Since it is possible to find the subsurface volume over any length of the furrow by defining P for that point, the incomplete Beta function is a useful relationship and can be written as:

$$\beta_i(P) = r \int_0^P (1-t)^{b'} t^{r-1} dt \qquad (23)$$

Gerards (1978) developed an empirical expression for the incomplete Beta function, but based his result on an assumption regarding the relationship between b' and r. Elliott and Walker (1980) report an evaluation of a proposal by Neff (1981) that the incomplete Beta function would be better represented by the first three terms in a binomial expansion of the function:

$$\beta_i(P) = P^r\left(1 - \frac{rb'}{r+1} P + \frac{rb'(b)}{2(r+2)} P^2\right) \qquad (24)$$

Equation 24 was found to be much easier to use and produces more accurate results than the method of Gerards (1978).

During the analysis of field data in this study, it was found that using Equation 6 to represent infiltration was nearly always inferior to the use of Equation 7 which in effect adds a term to describe steady-state infiltration. If the same mathematical procedures followed above are applied to the infiltration function as given by Equation 7 the steady-state factor is simply added to σ_m or $\beta_i(P)$. Neff (1981) shows the following for these parameters:

$$\forall_z(t_\ell) = (a' t_\ell^{b'} p t_\ell^{r}) W\sigma_m + c' t_\ell W\ell \frac{1}{r+1} \qquad (25)$$

and

$$\forall_z(t_L) = (a' t_\ell^{b'} p t_\ell^{r}) W\beta_i(P) + c' t_L WL(1 - \frac{r}{r+1} P) \qquad (26)$$

Equations 19, 21, 25 and 26 can be used to compute the individual areas in Figures 3 to 5 in order to determine the performance parameters. Values of a', b', p, and r are known. A summary of the formulas is given in Table 3.

FIELD DATA COLLECTION

Field data collection procedures were based on an evaluation program described by Ley (1978) with some minor modifications to account for farmer practices, labor availability, and time. This complete field data collection program is referred to as Procedure 4 in this text. A specific description of this procedure (as well as three simpler procedures) is given in Appendix B. The following summary of field data collection efforts and data analysis is taken from Neff (1981).

Summary of Field Work

Farmers cooperating in the research efforts were notified many months prior to the irrigation season of the nature and objectives of the field work. An interview with each farmer helped establish the history of irrigation and tillage practices for each field. Assurances were also given during the interview that efforts would be made to not hinder normal farm operations. Following these initial interviews, groups of three furrows were selected at each site to be representative of general field conditions. Four groups of furrows were selected at the Matchett farm to account for soil variability and differences in length of run. Two groups of three furrows were selected at the other sites. Each farmer had indicated in the interview that for at least a portion or all of the irrigation season, alternate furrow irrigation would be used. To accommodate this practice, two furrow layouts as shown in Figure 6 were used.

Advance furrows were chained, staked at 25 meter intervals, and surveyed to establish average field slopes. Soil moisture sampling, furrow cross-section sampling (with a profilometer), blocked furrow infiltrometer testing, and the setting of inflow and outflow flow measuring flumes were all accomplished on the day just prior to the first and subsequent irrigations. During the irrigation event, data collected included advance times to each 25 meter station, inflow and outflow discharge readings, and flow depth and top width measurements for selected stations. In addition, recession times were taken at each station following the termination of inflow.

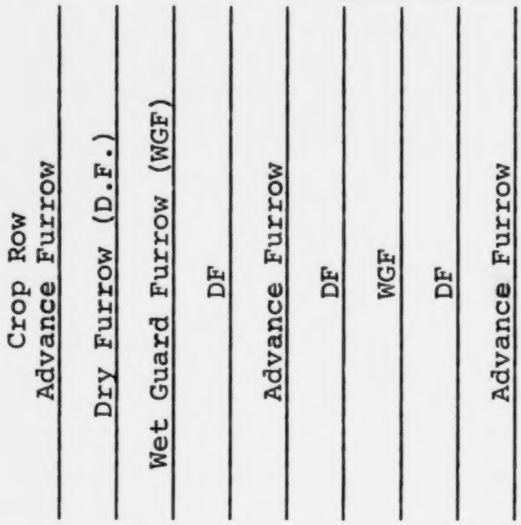
Gravimetric soil moisture samples, which were taken at representative stations along the furrow, included samples at several depths and at one or more locations in the cross-section at each station. Possible locations were the wet furrow bed, the crop row, and the dry furrow bed (if alternate furrow irrigation was the practice). Pre-irrigation samples were generally taken one or two days prior to the irrigation, and post-irrigation samples one to two days (depending on soil type) following the irrigation event.

TABLE 3. FORMULAS FOR THE AREAS REPRESENTED IN FIGURES 3, 4 AND 5.

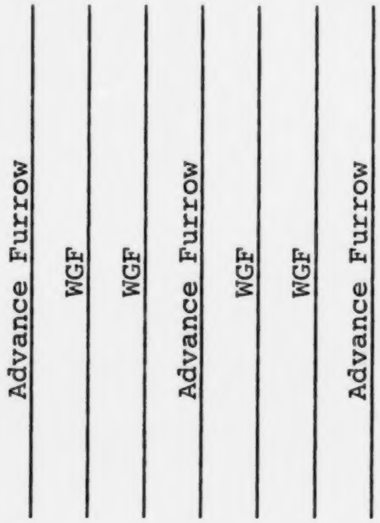
Area Description	For Infiltration Function $I = a't^{b'}$	For Infiltration Function $I = a't^{b'} + c't$
Complete and over-irrigation cases		
$A_1' + A_2' + A_3'$	$\forall_z(t_\ell) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \sigma_m$	$\forall_z(t_\ell) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \sigma_m + \frac{c't_\ell \cdot \ell}{1+r}$
$A_1' + A_2'$	$\forall_z(t_L) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(P)$	$\forall_z(t_L) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(P) + c't_\ell \cdot L(1 - \frac{r}{1+r} P)$
A_1'	$D \cdot L$	$D \cdot L$
Under-irrigation case		
$A_1' + A_2' + A_3' + A_5'$	$\forall_z(t_\ell) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \sigma_m$	$\forall_z(t_\ell) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \sigma_m + \frac{c't_\ell \cdot \ell}{1+r}$
$A_1' + A_2' + A_5'$	$\forall_z(t_L) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(P)$	$\forall_z(t_L) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(P) + c't_\ell \cdot L(1 - \frac{r}{1+r} P)$
$A_1' + A_2'$	$\forall_z(t_D) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(M_t)$[1]	$\forall_z(t_D) = a't_\ell^{b'} \cdot pt_\ell^r \cdot \beta_i(M_t) + c't_\ell \cdot x_D(1 - \frac{r}{1+r} P)$
A_1'	$x_D \cdot D$	$x_D \cdot D$

---

[1] $M_t = \frac{t_D}{t_\ell}$ where t_D is the time of advance to x_D.


Crop Row
Advance Furrow
Dry Furrow (D.F.)
Wet Guard Furrow (WGF)
DF
Advance Furrow
DF
WGF
DF
Advance Furrow

(a) Alternate furrow irrigation.


Advance Furrow
WGF
WGF
Advance Furrow
WGF
WGF
Advance Furrow

(b) Every furrow irrigation.

Figure 6. Location of advance furrows in field studies (from Neff, 1981).

Data on furrow cross-sectional shapes were obtained at several stations both before and after most irrigations using a profilometer consisting of movable rods mounted along a board at two centimeter intervals. The rods were graduated in centimeters and were placed in the furrow with the rods vertical and touching the soil surface. Then, either the rod heights were read directly or a photograph was taken for later analysis.

Blocked furrow infiltrometer tests were conducted one or two days prior to the irrigation by inserting two panels of sheet metal into the furrow at a spacing of one meter. The furrow bottom was covered with plastic and then filled with water to the desired depth. A hook gauge was positioned at this depth. The plastic was removed, and water was released from the supply reservoir to maintain a constant depth in the infiltrometer. Recorded data were the depth of water in the supply reservoir and the corresponding time. Knowing the cross-sectional area of the reservoir, these depths were later converted to volumes.

During advance, the time at which the water front reached each station was recorded. "Zero time" was the time at which the water reached station 0 + 00. Recession at each station was recorded as the time at which there was no longer water movement over the soil surface. Furrow outflow flumes were removed prior to the start of recession so that there would be no backwater effects.

Flow rates into and out of the test furrows were measured using either Cutthroat or trapezoidal flumes. The inflow flume was installed at station 0 + 00 and the outflow flume at the last measuring station in that particular furrow. Flume stage data were recorded periodically throughout the irrigation. The flumes were calibrated in the CSU Hydraulic Laboratory at the end of the irrigation season.

The depth and top width of furrow flow were measured at representative stations during the irrigation event. The flow depths were measured at approximately the furrow centerline. The times at which measurements started and ended in a particular furrow were recorded as elapsed times since the beginning of the irrigation.

At a time after the irrigation event when the root zone soil moisture was judged to be at field capacity, soil moisture samples and furrow cross-section measurements were again taken. Bulk density and soil analysis samples were taken once during the irrigation season. The textural classification of each soil sample was determined in the Colorado State University Soils Laboratory by the "hydrometer method."

Climatological data used for computing daily evapotranspiration (ET) were obtained from nearby weather observing stations at Greeley and Fort Morgan and from a weather station established adjacent to the Matchett field in Grand Junction. Daily ET was computed using the Penman Combination Method corrected for crop growth but not for moisture stress.

Problems in the Application of the Procedure

The major problem encountered in applying the evaluation procedure was the loss of data, particularly on the Matchett farm at Grand Junction. Decisions made by the farmer on short notice to account for changes in field conditions allowed little time for notification. The evaluation of several furrow groups was missed completely because the investigator was notified after an irrigation event had already begun. These episodes underscored the need for close cooperation and communication with the farmer if a complete evaluation is to be made.

Minor losses of data occurred not only for the above reason but also because of blockages of turnouts or tubes, careless handling of samples or equipment, improper sampling techniques and lack of sufficient labor to perform all aspects of the detailed evaluation procedure.

The labor problem was not evident until after the first or second irrigation event--too late to acquire additional personnel with sufficient irrigation knowledge. Each site had a team of one supervisor and two assistants to perform all tasks. This proved to be insufficient. Sharing of personnel at Greeley and Fort Morgan helped to somewhat alleviate this problem at those sites. The irrigation schedule of 24-hour sets and a shortage of help at critical times at the Grand Junction farm caused the elimination of evaluation tasks on a priority basis. Blocked-furrow infiltrometer tests were considered lowest priority and usually eliminated. Also, rather than taking both before and after irrigation furrow cross-sections and moisture samples, these quantities were sampled only once between irrigations if the furrow had not been disturbed in the intervening time. This practice was adopted at the other sites as well when simultaneous irrigations at both sites obviated the sharing of personnel.

Furrow cross-section data were occasionally lost because of poor quality or poorly processed slide pictures of the profilometer as placed and adjusted in the furrow. Although the procedure of photographing the profilometer offers an advantage in having a permanent record of data that can be reduced at ones leisure, the data can be lost completely if the pictures are improperly taken, processed or destroyed. This happened on at least two occasions at the Grand Junction site. Field reading of the profilometer directly onto the data forms was then initiated as a solution.

DATA REDUCTION

Data for all three sites were recorded on standardized forms, encoded, keypunched and then summarized. Analysis of the data provided the parameters necessary for the evaluation of irrigation performance at each site.

Advance and Recession Data

A power-law advance function in the form of Equation 8 was fit to all advance data using a two-point fit as suggested by Wilke (1973). Advance times and distances to the middle and end of the furrow were substituted into Equation 8 resulting in two simultaneous equations with the unknown quantities r and p. Solutions to the two equations can be obtained from:

$$r = \frac{\ln(0.5)}{\ln \frac{t_{0.5L}}{t_L}} \qquad (27)$$

and,

$$p = \frac{L}{{t_L}^{r}} \qquad (28)$$

where $t_{0.5L}$ is the time of advance to the mid-point of the field and t_L, again, is the advance to the field end. Elliott and Walker (1980) showed that the two-point fit results in smaller root-mean-square and average maximum absolute deviations from observed advance than did a regression technique fitting logarithmically transformed data to a line by least squares.

Recession data were used to help determine the volume of runoff after cutoff but was not analytically manipulated in an effort to predict recession. The runoff hydrograph at the last station was assumed to decrease linearly from the time of cutoff to the time of recession.

Soil Moisture Data

Determination of the soil moisture deficit (SMD) prior to irrigation is necessary for computing the time to infiltrate the deficit as well as the total water needed to fill the root zone to field capacity. When the time to infiltrate the deficit is compared to the difference between the time of cutoff and the time of advance, i.e., the opportunity time at the end of the field, then a determination can be made if the field has been over-irrigated or under-irrigated. This distinction makes a difference in the manner in which the efficiencies are calculated as noted previously.

Moisture deficits were determined in two ways. One method was by using actual soil moisture data while the other used values of daily evapotranspiration (ET) occurring between irrigations. Measured values of soil moisture content were determined gravimetrically. These values were converted to a volumetric basis using the measured soil bulk density. Total soil profile water content to 120 cm was then obtained. The difference in total soil profile water content just prior to irrigation and following by one day for the Printz farm and two days for the Benson and Matchett farms determined the deficit at each of three locations along the length of each furrow group. These deficits were averaged to obtain the SMD for each group of furrows. Where moisture samples were missing, or taken at times other than the day prior to irrigation and time of field capacity, daily ET was used instead of measured values. Table 4 shows values of the soil moisture deficits obtained by both methods.

TABLE 4. SOIL MOISTURE DEFICITS (IN MILLIMETERS).

		Benson		Printz		Matchett	
Irrigation	Group	ET	Measured	ET	Measured	ET	Measured
A	1	42.5	51.5	31.4	21.3	47.9	35.5
	2	42.5	39.9	38.1	35.9	39.5	38.2
B	1	49.2	44.6	32.6	47.4	11.6	20.7
	2	49.2	29.9	22.3	23.1	17.8	23.3
C	1	66.9	54.2	27.3	26.6	40.6	36.3
	2	66.9	45.2	21.5	35.0	40.7	36.4
D	1	44.4	37.5	52.3	60.0	43.2	28.2
	2	44.4	27.4	59.5	37.6	43.9	34.7
E	1	82.6	76.0	16.9	6.6	54.5	35.5
	2	82.6	71.2	20.9	12.3	54.0	46.4

Furrow Geometry

Flow depth, top width and furrow cross-sections are used to describe the geometry of furrows in the field. These data provided the basis for calculating average surface storage area during advance and the surface storage volume at the time of cutoff.

Equations for volume balance during advance used by Wilke and Smerdon (1965) and Ley (1978) all require knowledge of the average surface storage area during advance. A technique proposed by Salazar (1977) based on Manning's equation is used to determine this quantity.

The average furrow cross-sectional area and wetted perimeter of a furrow are assumed to be power functions of flow depths as given by:

$$A = AR\ d^{BR} \tag{29}$$

and,

$$WP = C_1 d^{e_1} \tag{30}$$

where,

A = the cross-section area;

WP = wetted perimeter;

d = depth of flow; and

AR, BR, C_1 and e_1 = constants obtained by fitting with field data.

The average surface storage area during advance can be found from

$$\bar{A} = (\sigma_y)(STC)\left(\frac{nQ}{S_o^{1/2}}\right)^{STE} \tag{31}$$

where

$\bar{A}$ = average surface storage area;

n = Manning's roughness coefficient;

Q = furrow inflow rate;

S_o = furrow slope; and

σ_y = mean surface storage area during advance to the surface storage area at the head of the furrow.

STC and STE are constants dependent only on furrow geometry and are given by

$$STC = AB\left(\frac{C_1^{2/3}}{AR^{5/3}}\right)^{STE} \tag{32}$$

$$STE = \frac{BR}{\frac{5BR}{3} - \frac{2e_1}{3}} \tag{33}$$

respectively.

To use Equation 31, σ_y was assumed to be 0.77 (values in the literature range from 0.75 to 0.8), and n was assumed to be 0.02. Wenstrom (1966) obtained values of Manning's roughness in furrows ranging from about 0.012 to 0.035 with an average of 0.020, on soils ranging from sandy loam to silty clay loam--the approximate range of soils investigated for this study.

Since $\bar{A}$ is the average surface storage area during advance, then the average surface storage area following advance should be larger. To account for this, $\bar{A}$ was multiplied by 0.9/0.77. This implies that the surface storage factor after advance increases to 0.9, as would physically be expected. Elliott and Walker (1980) found that the use of the 0.9 assumption had little influence on results of the volume balance calculations.

Inflow and Outflow

Inflow and outflow data were read from flumes in feet of head. Flow rates were obtained using the flume calibration for each flume. Hydrographs prepared from the flow rates and elapsed time of reading were then integrated by computer using the trapezoidal rule to obtain the total inflow (VIN) and outflow or runoff (VRO) volumes. During the recession phase, the outflow flumes were removed to prevent backwater effects. To account for runoff during recession, the rate of outflow was assumed to decrease linearly to the time that recession was complete.

Computation of Infiltration Parameters

The constants a', b' and c' in the "modified" Kostiakov cumulative infiltration equation (Eq. 7) were determined using a procedure similar to that suggested by Christiansen et al. (1966). Assuming a power-law advance, their volume balance equation was used in the form

$$\sigma_y a' t^{b'} = \frac{Qt}{x} - \frac{c't}{1+r} - \bar{A} \qquad (34)$$

where t and x are any advance time and corresponding distance of advance down a furrow.

A two-point method as used in obtaining the advance constants of Equation 7 was also used with an assumed value of c' to obtain a' and b'. Substitution of the known quantities of Q, r, $\bar{A}$ and the advance times and distance to the middle and end of the furrow resulted in two equations in two unknowns, a' and b', which were then calculated by simultaneous solution of the two equations.

Flume data of inflow and outflow volumes provide a convenient means of checking and adjusting the infiltration parameters obtained in the preceding manner. The difference in volumes between the inflow and outflow hydrographs at the time of cutoff represents not only the volume of water infiltrated to that point but also the amount of water in surface storage. This quantity, defined by

$$\begin{aligned} \text{VITOT} = {} & \text{Inflow volume} - \text{Outflow volume} \\ & \text{(both at time of cutoff, } t_\ell\text{)} \end{aligned} \qquad (35)$$

can be compared to the same volume computed using the incomplete Beta function solution to the volume balance equation plus the average surface storage volume. Generally, the predicted volume with c' = 0.0 is less than the measured volume. In that case, a new c' value can be chosen and the procedure for computing A and V and the predicted volume repeated until the measured and predicted volumes are nearly equal.

Infiltration parameters for a selected array of the furrows and irrigations evaluated are shown in Table 5. Several values of the infiltration exponent (b') are negative and, as such, indicate a very rapid decrease in infiltration rates toward the steady-state or c' value.

Computation of Performance Parameters

Computation of the infiltration parameters allow subsequent determination of the time to infiltrate the deficit (t_{SMD}) using Equation 7, the furrow width and the deficit. In turn, the time to infiltrate the deficit helps

TABLE 5. CONSTANTS FOR "MODIFIED" KOSTIAKOV CUMULATION INFILTRATION EQUATION (FROM NEFF, 1981).

Irrigation-Group	Furrow	BENSON FARM a'	BENSON FARM b'	BENSON FARM c'	PRINTZ FARM a'	PRINTZ FARM b'	PRINTZ FARM c'	MATCHETT FARM a'	MATCHETT FARM b'	MATCHETT FARM c'
A1	1	22100.	-.032	115.0	5750.	.604	0.0	11700.	.070	27.0
	3	17800.	.091	152.0	4410.	.501	0.0	3000.	.310	3.0
	5	28800.	.005	213.0	21400.	-.608	835.0	3600.	.407	23.0
A2	1	24100.	.019	99.0		-4.02	609.0	7380.	.102	27.0
	3	18400.	.048	93.0	36700.	-.267	556.0	9000.	.112	20.0
	5	18000.	.066	78.0	6240.	.622	0.0	1160.	-.007	32.0
B1	1	19800.	.059	76.0	3690.	.725	0.0	9100.	.087	21.0
	3	10900.	.273	89.0	43200.	-.292	597.0	3290.	.334	0.0
	5	25900.	-.017	135.0	14500.	.063	481.0	3830.	.301	15.0
B2	1	50900.	.413	0.0	22500.	.039	343.0	2240.	.393	0.0
	3	87700.	.200	67.0	28300.	-.084	465.0	2990.	.348	10.0
	5	13600.	.124	98.0	47200.	-.208	613.0	2160.	.416	2.0
C1	1	63400.	-.108	102.0		-1.120	838.0	5180.	.158	14.0
	3	38700.	-.040	147.0	37700.	-.372	386.0	4570.	.194	17.0
	5	113000.	-.335	159.0	30600.	-.175	343.0	3550.	.202	28.0
C2	1	77700.	-.274	96.0	655.	-.556	387.0	2350.	.355	0.0
	3	6440.	.400	0.0	48000.	-.330	472.0	2860.	.322	14.0
	5	12300.	.189	88.0		-1.10	682.0	2590.	.339	5.0
D1	1	2090.	.369	55.0	56300.	-.060	623.0	5500.	.138	17.0
	3	9730.	-.237	138.0	57000.	-.310	462.0	5730.	.136	17.0
	5	7140.	-.160	131.0	7390.	.415	240.0	3180.	.253	21.0
D2	1	17900.	-.277	89.0	137000.	-.671	614.0	3360.	.247	13.0
	3	11000.	-.095	96.0	75600.	-.425	511.0	2940.	.335	13.0
	5	9730.	-.043	121.0	167000.	-.888	834.0	3340.	.289	11.0
E1	1	35400.	-.113	112.0	49400.	0.571	669.0	3550.	.208	7.0
	3	34000.	-.175	149.0	20100.	-.471	345.0	3090.	.228	11.0
	5	50200.	-.324	160.0	36700.	-.636	432.0	2570.	.249	16.0
E2	1	12800.	.110	63.0	39000.	-.348	440.0	5210.	.141	32.0
	3	11000.	.149	80.0	21100.	-.085	420.0	1910.	.376	3.0
	5	22900.	-.060	118.0	95600.	-.553	641.0	3510.	.228	19.0

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determine whether a case of an under-irrigation or over-irrigation has occurred and finally the approach needed to compute the performance parameters of Equations 10 to 15.

The time of cutoff (t_ℓ) and the opportunity time at the end of the field ($t_\ell - t_L$) besides the time to infiltrate the deficit are also necessary to ascertain which case has occurred. The distribution profiles in Figures 3 to 5 illustrate the under- and over-irrigation cases as well as the case of a "complete" irrigation. Each case is defined by relationships between the times as follows:

Case 1. If $(t_\ell - t_L) > t_{SMD}$, the furrow is over-irrigated.

Case 2. If $(t_\ell - t_L) = t_{SMD}$, the furrow has a "complete" irrigation.

Case 3. If $(t_\ell - t_L) < t_{SMD}$, the furrow is under-irrigated.

Performance parameters can be determined for Cases 1 and 2 using volumes from inflow-outflow flume data. For Case 3, the computation is based not only on flume data but also on infiltrated volumes computed using the appropriate form of the incomplete Beta function solutions. The surface storage volume that does not runoff following the time of cutoff can be distributed over the length of the furrow assuming a triangular distribution. Employing these methodologies, values for E_a, DPR and TWR for the evaluated furrows representing the measured performance were computed and are presented in Table 6.

TABLE 6. PERFORMANCE PARAMETERS (DECIMAL) REPRESENTING MEASURED PERFORMANCE FOR PROCEDURE 4 (FROM NEFF, 1981).

Irrigation-Group	Furrow	BENSON FARM			PRINTZ FARM			MATCHETT FARM		
		E_a	TWR	DPR	E_a	TWR	DPR	E_a	TWR	DPR
A1	1	0.498	0.301	0.201	0.509	0.039	0.452	0.160	0.658	0.182
	3	0.409	0.202	0.389	0.831	0.169	0.000	0.146	0.807	0.047
	5	0.356	0.111	0.532	0.889	0.106	0.005	0.141	0.437	0.422
A2	1	0.588	0.204	0.208	0.376	0.077	0.547	0.148	0.626	0.226
	3	0.442	0.401	0.157	0.535	0.023	0.443	0.153	0.645	0.202
	5	0.436	0.451	0.113	0.292	0.019	0.689	0.107	0.718	0.176
B1	1	0.726	0.274	0.000	0.250	0.001	0.749	0.094	0.542	0.364
	3	0.516	0.227	0.258	0.555	0.049	0.396	0.094	0.625	0.282
	5	0.568	0.264	0.169	0.526	0.057	0.417	0.087	0.489	0.425
B2	1	0.942	0.059	0.000	0.380	0.079	0.541	0.147	0.628	0.225
	3	0.855	0.145	0.000	0.367	0.025	0.608	0.127	0.536	0.337
	5	0.756	0.168	0.076	0.305	0.039	0.656	0.131	0.561	0.309
C1	1	0.801	0.199	0.000	0.463	0.010	0.527	0.343	0.618	0.039
	3	0.637	0.326	0.037	0.654	0.178	0.168	0.328	0.564	0.108
	5	0.710	0.286	0.004	0.659	0.122	0.219	0.318	0.461	0.221
C2	1	0.872	0.128	0.000	0.466	0.121	0.413	0.288	0.712	0.000
	3	0.962	0.038	0.000	0.368	0.031	0.601	0.287	0.560	0.153
	5	0.875	0.125	0.000	0.318	0.025	0.656	0.342	0.598	0.060
D1	1	0.561	0.439	0.000	0.423	0.013	0.564	0.367	0.572	0.061
	3	0.549	0.416	0.035	0.772	0.037	0.191	0.338	0.608	0.054
	5	0.587	0.404	0.010	0.703	0.012	0.285	0.288	0.572	0.141
D2	1	0.776	0.224	0.000	0.762	0.058	0.180	0.420	0.544	0.036
	3	0.769	0.231	0.000	0.817	0.068	0.116	0.324	0.529	0.147
	5	0.801	0.199	0.000	0.616	0.010	0.374	0.347	0.582	0.071
E1	1	0.738	0.263	0.000	0.360	0.013	0.628	0.330	0.670	0.000
	3	0.636	0.364	0.000	0.514	0.192	0.294	0.325	0.675	0.000
	5	0.681	0.319	0.000	0.570	0.030	0.400	0.369	0.631	0.000
E2	1	0.842	0.158	0.000	0.455	0.023	0.522	0.328	0.538	0.134
	3	0.882	0.118	0.000	0.387	0.066	0.547	0.317	0.684	0.000
	5	0.825	0.175	0.000	0.313	0.042	0.645	0.386	0.586	0.028

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SECTION V

THE COST-EFFECTIVENESS OF ALTERNATE EVALUATION PROCEDURES

INTRODUCTION

Large-scale studies of furrow irrigation systems in sufficient detail to define each of the major variables discussed in the previous sections are prohibitively expensive in most cases. As a result, four alternative evaluation procedures were organized that would span the range of detail that might be required for most field situations. Three of these procedures were simplifications of the complete evaluation methodology. The costs of each procedure, described as Procedures 1 through 4 in Appendix B, were developed in order to test the cost-reliability of the alternatives to Procedure 4, which is the most detailed procedure. A summary of this costing data is given in Appendix C.

The other dimension of a field evaluation project concerns the spatial resolution and density of measurements and their effect on adequacy of the evaluation. Neff (1981) analyzed both the importance of evaluation methodology and the space-density factors. This section is taken directly from his results.

DESCRIPTION OF ALTERNATE EVALUATIONS

Each alternate procedure was devised to either utilize data available from the detailed furrow evaluation described in Sections IV and VI, or data available in the literature. Advance times and distances to the middle and end of the field, the time of cutoff and basic site data are common to all the procedures. The following sections describe how data not common to each procedure were determined.

Estimating a Value for c'

Procedures 1 and 2 require an estimate of the value of c' in the "modified" Kostiakov cumulative infiltration equation. Soil information from the Colorado Soil Guides and ranges of basic intake rates from Pair et al. (1975) were used to estimate c'. The low value of each range was selected for the c' value as a conservative estimate, except in the case of the Grand Junction soil. Observed field conditions through the season on the Matchett farm were poor enough to warrant even further reduction in the basic intake rate. The c' values estimated from this information were 32, 65 and 325 cm^3/min/m for the Matchett, Benson and Printz farms, respectively. The c' value for Procedure 3 is obtained in the same manner as for Procedure 4 described in Section IV.

Estimating Soil Moisture Deficits

An estimate of the soil moisture deficits based on the "feel method" and "book" values of total available water (TAW) was required for Procedures 1 and 3. An individual with experience was assumed capable of estimating the percentage of TAW depleted to the nearest 25 percent by the "feel" of the soil. Measured values of the percentage of depletion were used to simulate expected values of the soil moisture deficit obtained by the "feel method." When the measured percent of TAW depleted was less than 12.5 percent, the SMD was assumed at 10 percent of the "book value" of TAW. Again, the Colorado Soil Guides provided the book values for TAW for the studied soils.

Measured soil moisture deficits found by considering the samples taken only near the head and the end of the field were used for Procedure 2. The deficits were computed in the same manner as described in Section IV except that only the two locations were averaged. Table 7 shows the simulated deficits for both methods (measured soil moisture deficit, SMD, based on gravimetric samples and estimated SMD using evapotranspiration data) and their deviations from the ET determined deficits, which were considered the more reliable data.

To provide an evaluation of the deviation of average soil moisture content in the field profile, deviations for combinations of 1, 2, 3, and 4 locations were compared against six locations. The absolute fractional deviation from the standard of six locations was calculated for each combination of 1, 2, 3 and 4 locations. The soil moisture data collected for all five irrigation events monitored at each farm were used. Figures 7 to 9 indicate that a sampling at one location should be within 10 to 15 percent of the field profile moisture content.

Estimating Average Surface Storage Area

The average surface storage area $(\bar{A})$ for Procedures 1 and 3 were estimated from available depth and top width data taken at the station nearest the inflow flume. The furrow was assumed to be described as an approximate, parabolic, prismatic channel such that the cross-sectional area near the head of the furrow could be computed by

$$A = 2/3\ Td \qquad (36)$$

where T is the top width and d is the depth. Multiplication of this area by the surface storage factor of 0.77 gave $\bar{A}$.

Values of $\bar{A}$ for Procedure 2 were found from measurements of the furrow cross-sections (by profilometer) and depths of flow taken at the station nearest the inflow flume. Before and after profilometer information was used to obtain a relationship for the average cross-sectional area in the form of Equation 29. The average of the depths of flow was substituted to find the actual value for the area and this, in turn, multiplied by the surface storage factor.

TABLE 7. SOIL MOISTURE DEFICITS AND DEVIATIONS FROM ET DETERMINED DEFICITS (FROM NEFF, 1981).

		BENSON		PRINTZ		MATCHETT	
Irrigation	GRP	Estimated SMD	SMD-Measured Head & End	Estimated SMD	SMD-Measured Head & End	Estimated SMD	SMD-Measured Head & End
A	1	46.5	53.2	31.5	18.2	54.0	52.1
	2	46.5	20.6	31.5	44.6	54.0	43.6
B	1	46.5	45.8	31.5	50.2	21.6	34.5
	2	46.5	35.6	31.5	27.7	21.6	30.9
C	1	93.0	47.2	31.5	24.6	54.0	35.0
	2	93.0	61.7	31.5	26.0	54.0	48.2
D	1	46.5	41.0	31.5	63.5	54.0	42.5
	2	46.5	36.4	63.0	44.2	54.0	34.7
E	1	93.0	74.8	12.6	9.2	108.0	39.4
	2	93.0	83.7	12.6	14.4	54.0	48.5
Average Absolute Fractional Deviation		0.1425	0.2847	0.2350	0.2919	0.3689	0.3828

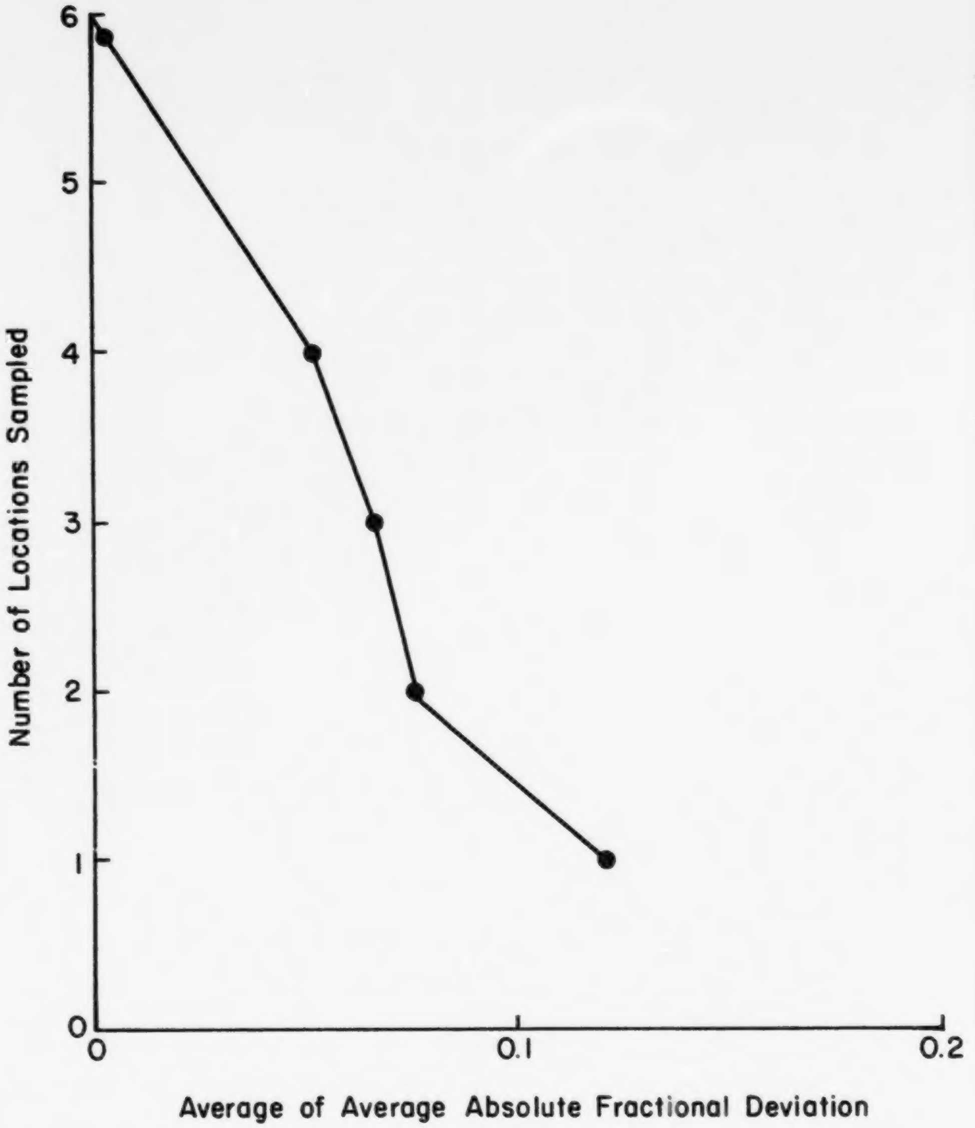

Figure 7. Average of deviations from field average profile moisture content at the Benson farm (from Neff, 1981).

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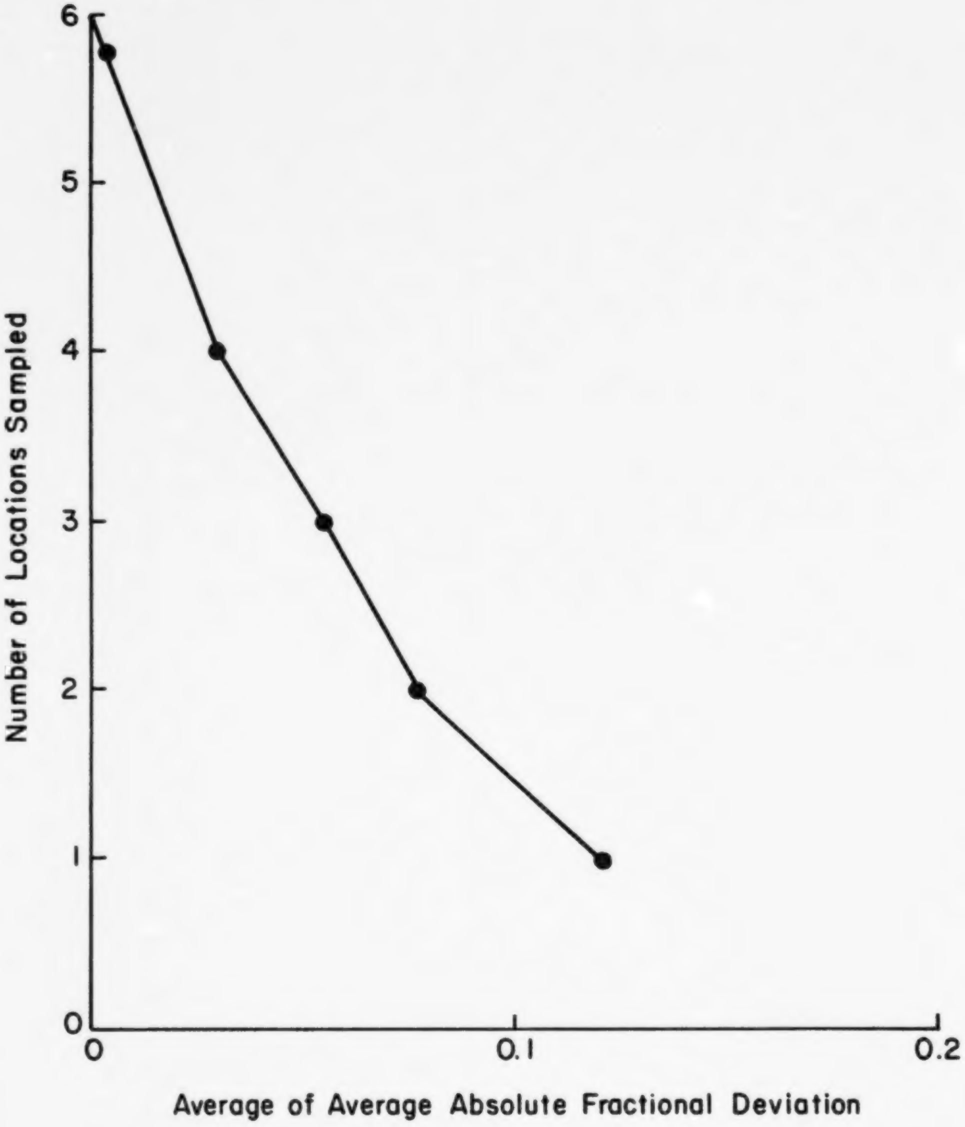

Figure 8. Average of deviations from field average profile moisture content at the Printz farm (from Neff, 1981).

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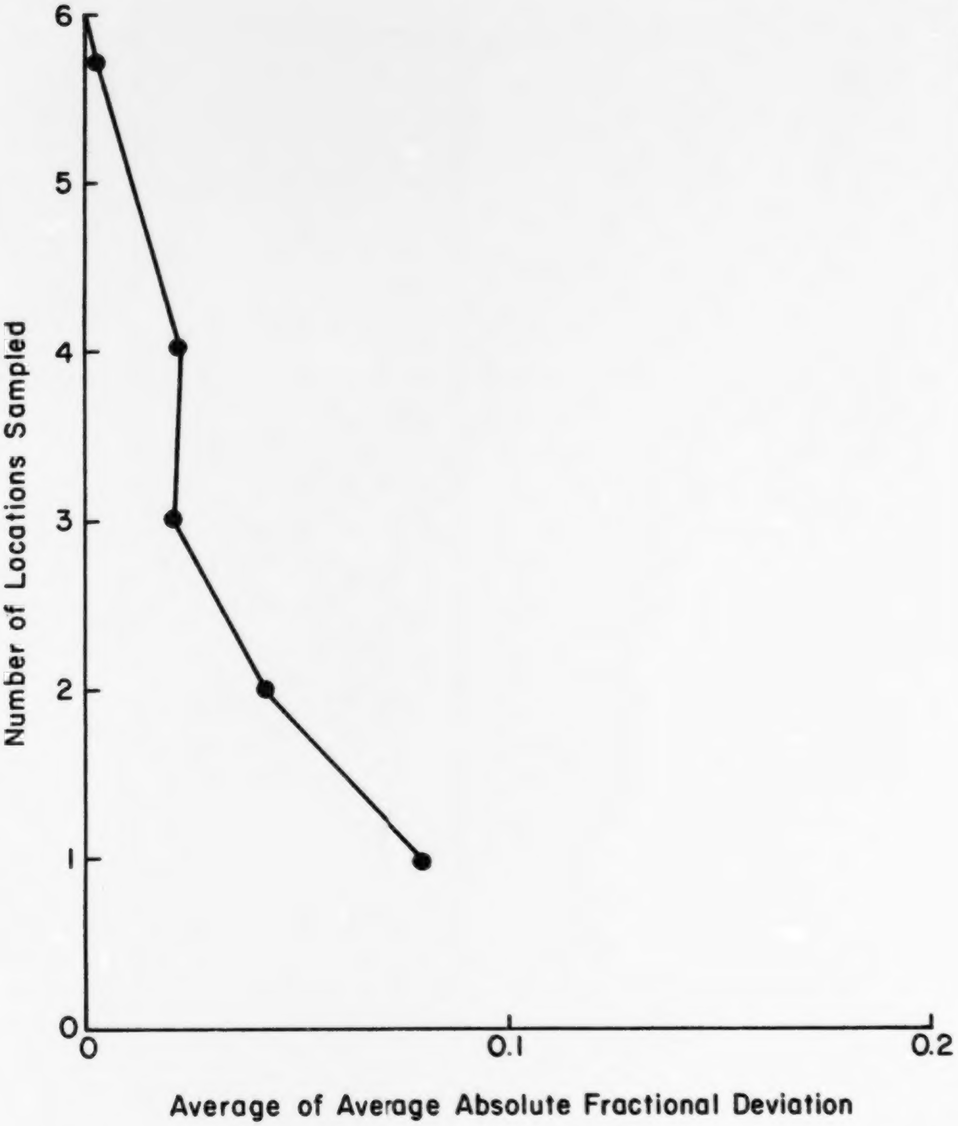

Figure 9. Average of deviations from field average profile moisture content at the Matchett farm (from Neff, 1981).

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The average absolute deviations of the storage areas found by each procedure as compared to the measured values used in Procedure 4 are listed in Table 8.

TABLE 8. DEVIATIONS OF PREDICTED SURFACE STORAGE AREAS.

Farm	Average Surface Storage Area, cm^2	Deviations in cm^2	
		Procedure 1 & 3	Procedure 2
Benson	55.8	0.171	0.222
Printz	97.2	0.255	0.602
Matchett	19.0	0.206	0.266

Inflow Estimates

Procedure 1 was the only procedure requiring an estimate of inflow since flume data were available in all other procedures. To simulate this estimation, measured flow rates for each furrow were averaged by group. This quantity was then rounded to the nearest one-fourth liter per second if the flow exceeded 1 lps and to the nearest 0.1 lps for flows less than 1 lps. The value of inflow rate (Q) obtained in this manner was then used as the estimator for all furrows in the group.

Actual field estimates, of course, would be performed by dividing the number of outlets (tubes or gates) by the total flow, by measuring the elevation or pressure head and size of outlet and using a flow calibration curve. A combination of both methods may be used where one can serve as a check on the other.

The average absolute percent deviation of the estimated from the measured inflow for each furrow was 15 percent, 12.2 percent, and 9.2 percent for the Benson, Printz and Matchett farms, respectively.

Computing Predicted Performances

Infiltration coefficients for furrows evaluated by Procedures 1 and 2 were easily obtained using the assumed value of c' without the necessity of the iterative technique described in Section IV. However, volumes necessary to compute the performance parameters could only be found using the incomplete Beta function solutions for volume balance discussed in Section IV. The lack of outflow data for these first two procedures also precluded the measurement of the amount of surface storage volume (SSU) that became tailwater. To account for this, one-half of the SSU was assumed to run off while the other half infiltrated the field. A triangular distribution was again assumed for the infiltrated portion.

ANALYSIS OF PROCEDURAL VARIATION

The deviation of the measured performances of individual furrows, combinations of furrows, and irrigations from the site average performance of all five evaluated irrigations was used as an indicator of the procedural variation or error. This deviation is defined as:

$$AAFD = \frac{\Sigma \left| \frac{P-M}{M} \right|}{N} \qquad (37)$$

in which,

AAFD = average absolute fractional deviation;

P = predicted parameter value;

M = measured parameter value; and

N = number of data.

Combinations of furrow performance considered for comparison with the site average measured performance were combinations of two and three furrows grouped as shown in Figure 6, or four furrows equally spaced in separate groups of two. Assuming at least two furrows would generally constitute a group to minimize experimental variation, combinations of two furrows as well as "odd" combinations of three and five furrows between groups were not considered. All combinations of two, three and four irrigations were considered.

A similar analysis was undertaken comparing the combinations of performances against the average performance for the respective irrigation. An average of the average absolute fractional deviation was obtained for each combination over the five irrigations.

Procedural variations were the highest for the Matchett farm largely because of the change made by the farmer in flow rates after Irrigation 3. The resulting flow rate reduction reduced the runoff, thereby increasing the application efficiency from 10-15 percent to 30-35 percent. The comparison of individual irrigations shows that the average of deviations was less than 10 percent from the measured average.

Flow rate variations appear to also be largely responsible for the deviations found at the Benson and Printz farms. Adjustments were made to the flow on these two farms to create a greater variation in variables. Unfortunately, these variations mask deviations that could also be due to other causes.

Figures 10 to 12 are plots of the average of the deviations of the different levels of evaluation (1, 2, 3, 4 or 6 furrows) from the average measured irrigation performances. The same assumptions were made in combining the performances of the predicted furrows as were used earlier, except that the combination or average of all six furrows could be compared. Figures 13 to 15

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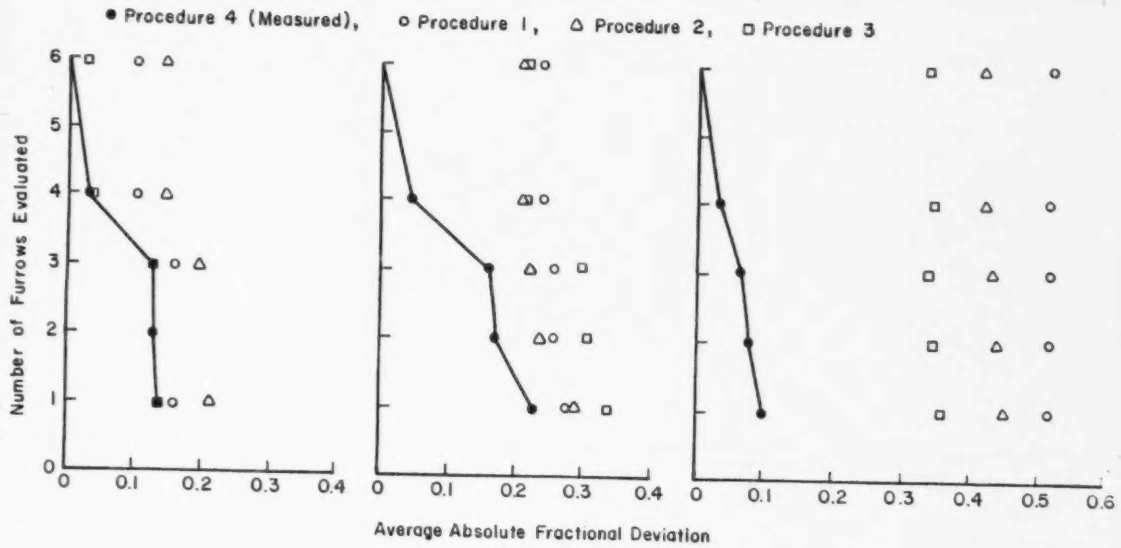

(a) Benson Farm

(b) Printz Farm

(c) Matchett Farm

Figure 10. Comparison of irrigation application efficiencies at the three farms (from Neff, 1981).

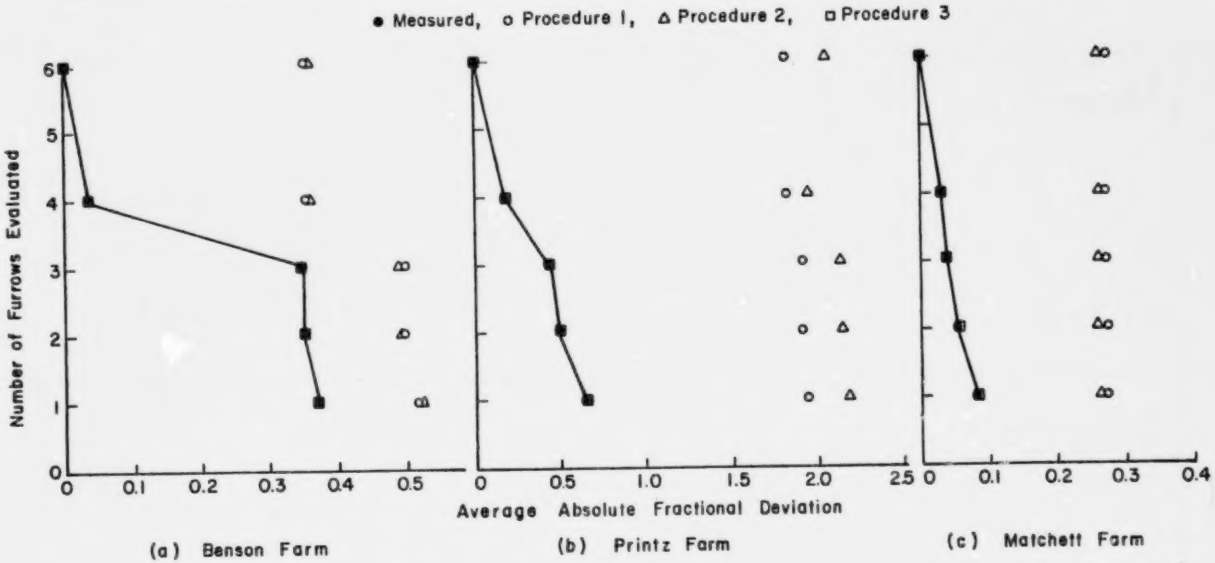

Figure 11. Comparison of tailwater ratios at the three farms (from Neff, 1981).

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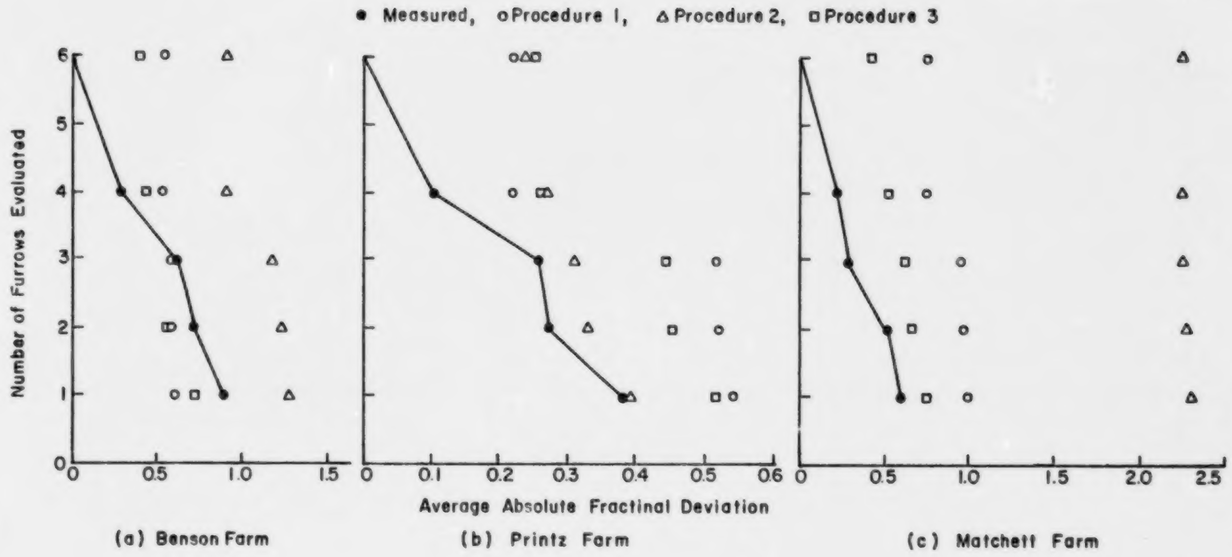

(a) Benson Farm

(b) Printz Farm

(c) Matchett Farm

Figure 12. Comparison of deep percolation ratios at the three farms (from Neff, 1981).

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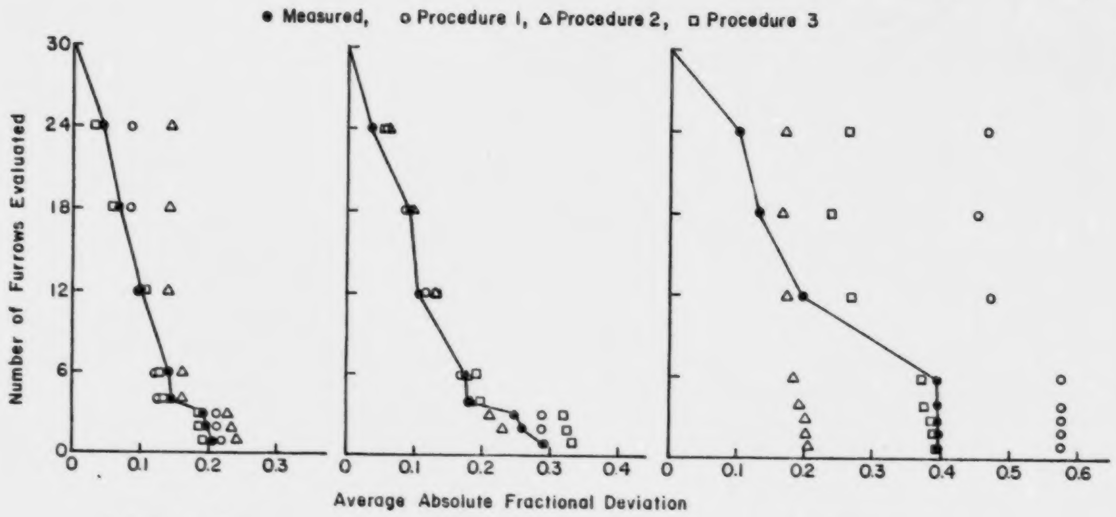

(a) Benson Farm (b) Printz Farm (c) Matchett Farm

Figure 13. Site comparison of application efficiencies at the three farms (from Neff, 1981).

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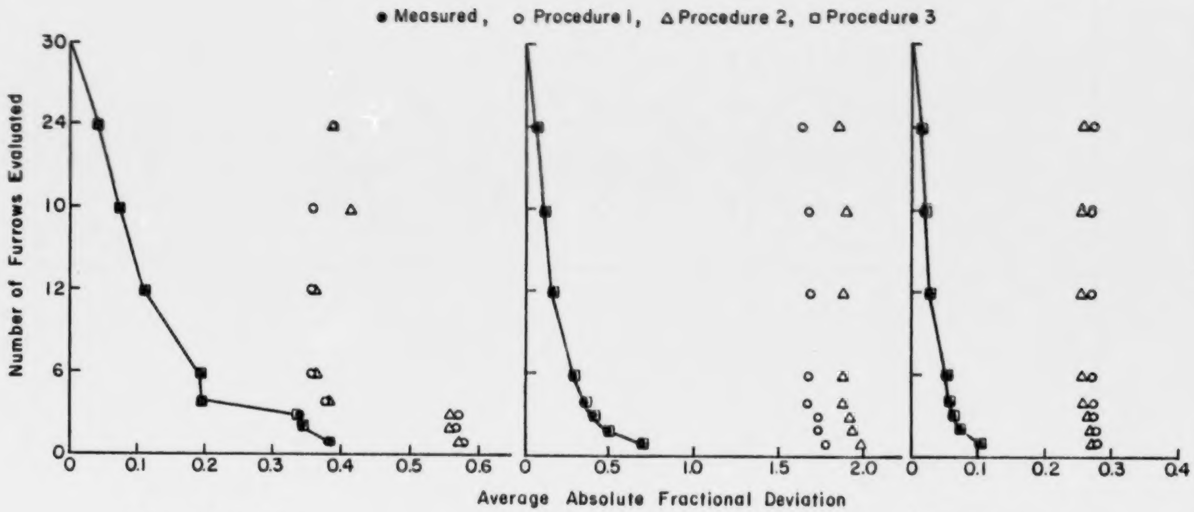

(a) Benson Farm (b) Printz Farm (c) Matchett Farm

Figure 14. Site comparison of tailwater ratios at the three farms (from Neff, 1981).

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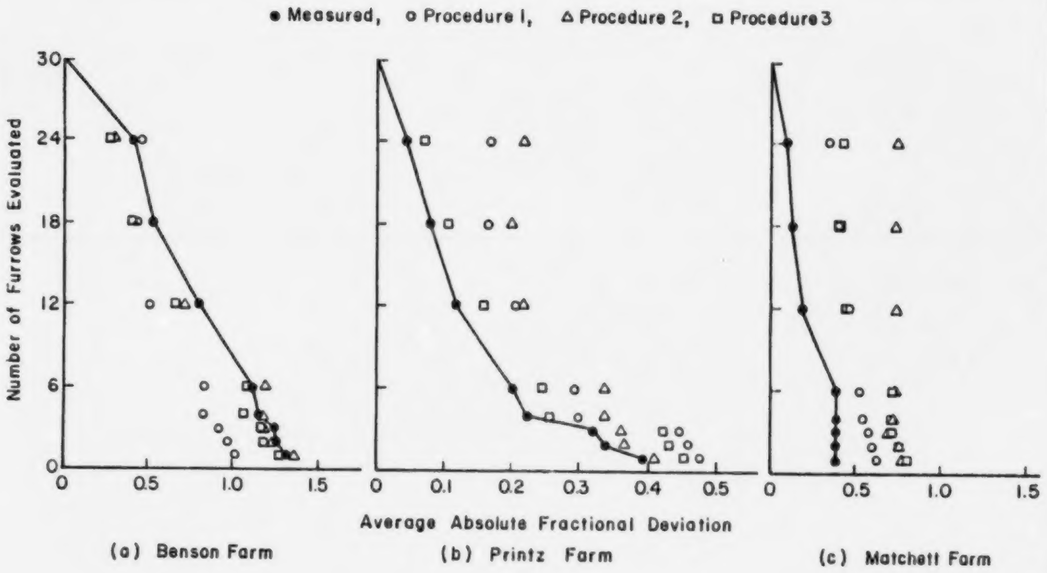

(a) Benson Farm (b) Printz Farm (c) Matchett Farm

Figure 15. Site comparison of deep percolation ratios at the three farms (from Neff, 1981).

show plots of the deviations from the measured site average performances for the combinations of furrows and irrigations. The average of all individual performances for five irrigations was also used for comparison.

Comparison of Predicted Performances to Measured Irrigation Averages

Comparisons of predicted values with the measured irrigation average for the application efficiencies are shown in Figure 10. Procedure 3 predicts this efficiency better than do Procedures 1 and 2 for the Benson and Matchett farms, but does not predict the Printz farm well until at least four furrows are evaluated. Flume outflow data are available for Procedure 3, and one would expect this procedure to predict the average tailwater ratio for an irrigation exactly. Figure 11 shows this to be the case. Deviations of the deep percolation ratios for each procedure follow the same trend as the application efficiencies (see Figure 12).

Comparison of Predicted Performances to the Measured Site Averages

The site average application efficiency is predicted best by Procedure 3 for the Benson farm (Figure 13a) and by Procedure 2 at the Printz and Matchett farms (Figures 13b and 13c). In fact, Procedure 2 predicts the site average application efficiency better than does Procedure 4 for the Matchett farm. Since Procedure 2 does not predict the irrigation average application efficiency well for this farm, offsetting errors are the likely cause of this circumstance.

For all farms, Procedure 3 is the best predictor of the site average tailwater ratio as seen in Figure 14.

The site average deep percolation ratio is predicted best for the Benson farm by Procedure 1 when two irrigations or less are evaluated. Procedure 3 is nearly as good as Procedure 1 at the Benson farm, but is the best predictor for more than three furrows for the Printz farm, and is equal to Procedure 1 when at least 12 furrows are evaluated for the Matchett farm. Figure 15 shows these comparisons.

A comparison of the predicted performance of each procedure to the measured performance on a furrow-by-furrow basis indicated that Procedure 3 predicted all performance parameters best for the Benson and Matchett farms but only about equally as well as Procedure 2 for the Printz site.

Table 8 showed the averages of the deviations in surface storage area, $\overline{A}$, for each farm and performance parameters compared furrow-by-furrow. While making this analysis, deviations were considered to be zero when both the predicted and measured values were zero. In cases where the measured performances were zero, thus causing an undefined quantity in Equation 36, the comparison was ignored and not included in the average.

EVALUATION COSTS FOR ALL PROCEDURES

The costs associated with the use of each procedure are included in Appendix C. Estimates of the costs in terms of hours of labor and equipment

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needs were based on costs accruing to the actual detailed furrow evaluation procedure. Rather than apportion hourly costs between those of a supervisor and one or two assistants, the hourly wage was estimated as seven dollars ($7) per hour. Equipment costs were obtained from catalogs for equipment available in the spring of 1980. Costs for major items were apportioned over an estimated useful life on an annual basis without using a capital recovery factor. All costs, of course, will vary due to differences in labor, equipment, shipping and inflation between areas.

The costs of applying each procedure for one furrow up to five irrigations are plotted versus the deviations from the measured site average performances in Figures 16 to 18. The points on the figures representing Procedure 4 are connected to serve as a visual reference for analysis.

Procedure 1 appears capable of predicting the application efficiency (Figures 16a and 16b) within 10 percent with the least cost except at the Matchett farm. Procedure 2 does best at the Matchett site (Figure 16c), but considering that its values are a result of offsetting error, Procedure 3 is the next best. In all three locations, Procedure 3 is consistently less expensive and is at least as accurate as Procedure 4.

The tailwater ratio (Figure 17) is predicted best by Procedure 3, the only procedure other than Procedure 4 capable of predicting this parameter within less than 10 percent error at all farms.

The deep percolation ratio at the Benson and Printz farms (Figures 18a and 18b) is predicted with Procedure 3 at less than 20 percent error providing sufficient evaluations are made (two irrigations at Printz and five irrigations at Benson). None of the procedures can predict the Matchett deep percolation (Figure 18c) at less than 20 percent error except for Procedure 4 with at least four irrigations evaluated.

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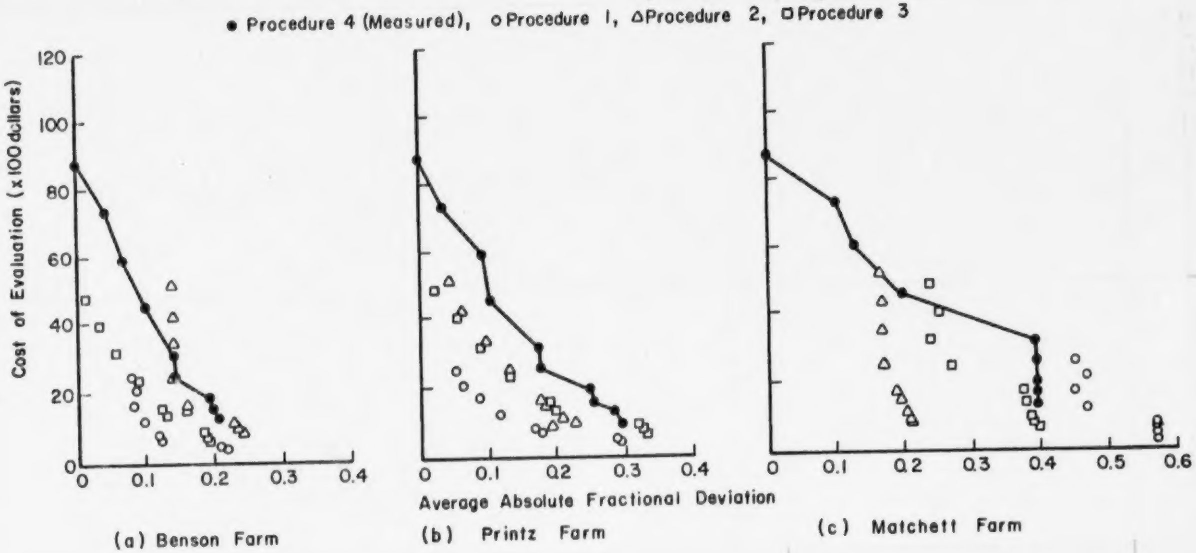

(a) Benson Farm (b) Printz Farm (c) Matchett Farm

Figure 16. Cost comparison for application efficiencies at the three farms (from Neff, 1981).

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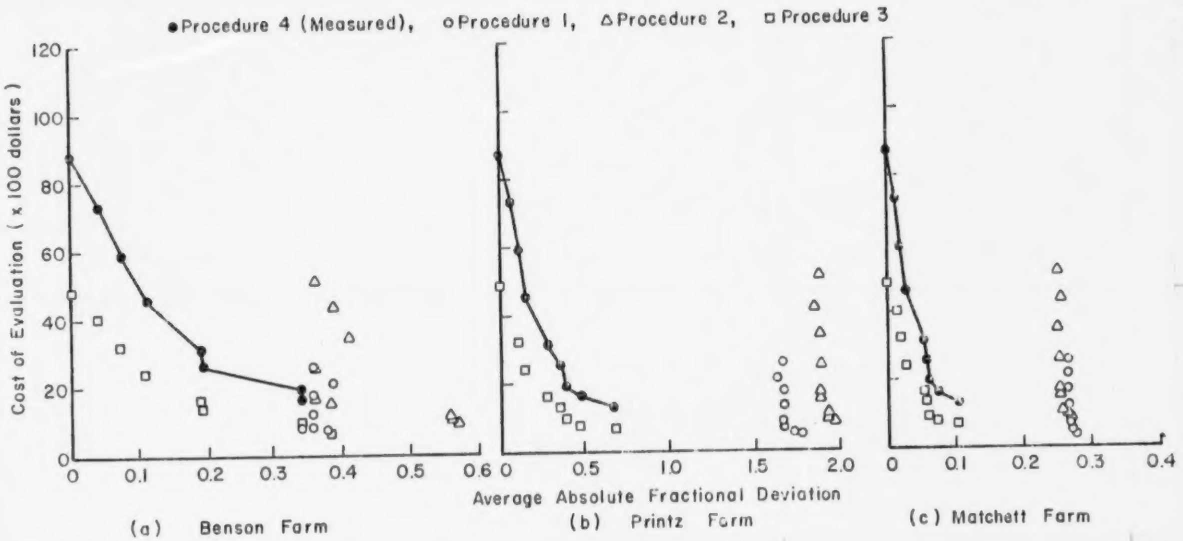

Figure 17. Cost comparison for tailwater ratios at the three farms (from Neff, 1981).

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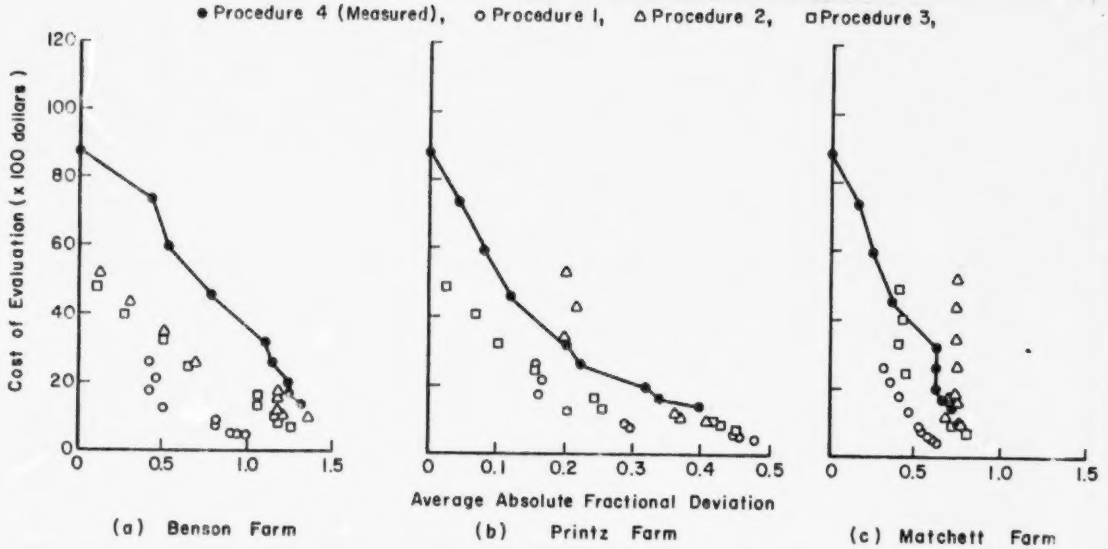

Figure 18. Cost comparison for deep percolation ratios at the three farms (from Neff, 1981).

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SECTION VI

A VOLUME-BALANCE MODEL OF FURROW IRRIGATION PERFORMANCE

INTRODUCTION

Once the field evaluation has been made, the next step in the planning process is to assess the alternatives for improving the system's performance. The improvement alternatives include: (1) change the physical nature of the system by changing the field length or slope, including cutback and tailwater reuse systems, or convert the irrigation system to a sprinkler or trickle system; and (2) improve the management of the existing system by adjusting furrow inflow rates, time of inflow, and soil moisture deficit at the time of irrigation, etc. The improvements stemming from physical rehabilitation and change can be determined rather easily from the field evaluation data. The writers have discussed these assessments in several literature sources (Evans et al., 1981).

The problem of improving furrow irrigation performance by changing water management practices is a relatively difficult problem since the field evaluation data must be sufficient to allow the interrelationships among the individual parameters to be adequately defined. Binder (1981) used the basic volume balance approach and the field data from the Benson, Printz, and Matchett fields to formulate a furrow irrigation performance model. This section presents his results.

MODEL DESCRIPTION

The empirically based simulation model (Program FURSIM) was developed as a furrow irrigation performance simulator using a separation of variables into "states" and "decisions." Decision variables are the controllable or partially controllable system inputs. State variables are the variables representing the system at any time and place depending upon the corresponding decision variable. An example of a decision variable in a furrow irrigation system is the furrow discharge. The resulting state variables include the functions describing the infiltration and advance characteristics. Program FURSIM determines system performance as a function of the four primary decision variables: furrow inflow rate, time of cutoff, soil moisture deficiency at time of irrigation, and number of previous irrigations. State variables chosen to remain constant for the system include furrow spacing, slope, and length. Program FURSIM has been developed based on 110 comprehensive furrow evaluations performed over a three-year period at the three fields described earlier.

The measured data were fit to a series of empirical equations enabling the state variables to be described as a function of the decision variables. The basic equations for characterizing the flow of water in a furrow were described in Section IV. A simplified flow chart for Program FURSIM is shown in Figure 19.

Simulation of Furrow Geometry

The model utilizes the parabolic furrow geometry functions as expressed in Equations 29 and 30. Previous studies, field observations, and evaluation of the furrow geometry data show that a particular furrow cross-section does not remain constant throughout the irrigation season. The seasonal change in furrow cross-section is illustrated in Figure 20. The model accounts for the change in furrow cross-section by holding the BR coefficient of Equation 29 constant and varying the AR coefficient throughout the irrigation season. The value for BR is the representative value as determined for the first irrigation. The measured AR values are then adjusted such that the AR values at a typical depth of flow are the same as if the measured AR and BR values were used. A relationship for the adjusted AR values as a function of irrigation number is determined by performing a least squares regression and has the form:

$$AR' = ARC1(N_i)^{ARC2} \tag{38}$$

where,

AR' = adjusted value of AR,

$ARC1$, $ARC2$ = empirical coefficients, and

N_i = irrigation number.

The representative BR values for the Benson-79, Matchett and Printz sites are 1.56, 1.62, and 1.44, respectively. The adjusted AR functions for the three sites are shown in Figure 21.

Furrow Roughness

The model uses Manning's roughness factor (n) to describe the furrow roughness. Analysis of the measured n values resulted in no representative relationship between furrow roughness and the decision variables being developed. This is primarily due to the evaluation not being adequately designed for developing such a relationship. The data analysis also revealed that no apparent relationship between furrow roughness and soil type was found to exist. Wenstrom (1966) also observed that furrow roughness could not be related to soil type. Consequently, a constant n value of 0.02 is used in Program FURSIM for all three sites. This value is based on the site data and n values reported by Ley (1978), Salazar (1977), and Wenstrom (1966).

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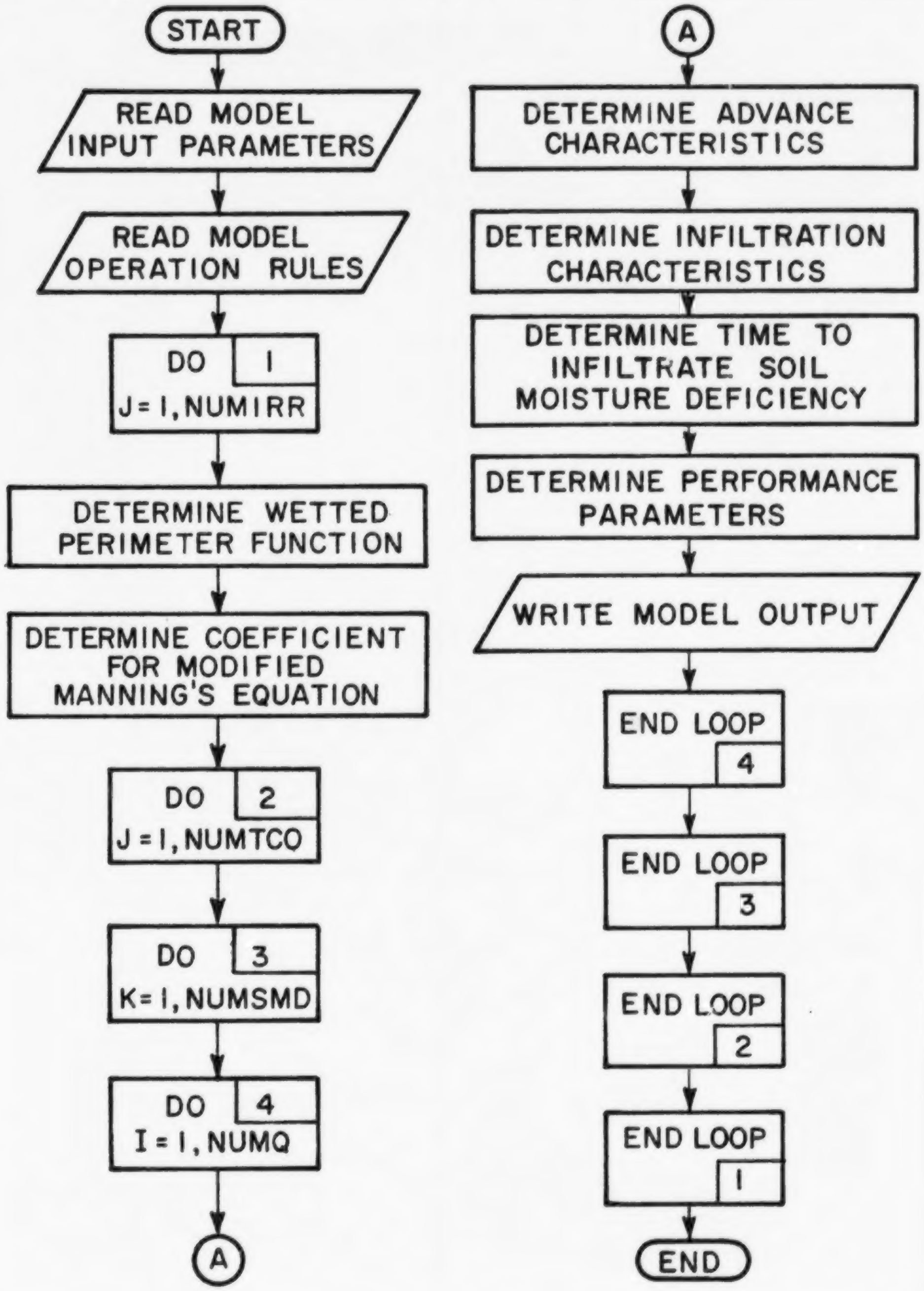
START
READ MODEL INPUT PARAMETERS
READ MODEL OPERATION RULES
DO 1
J = 1, NUMIRR
DETERMINE WETTED PERIMETER FUNCTION
DETERMINE COEFFICIENT FOR MODIFIED MANNING'S EQUATION
DO 2
J = 1, NUMTCO
DO 3
K = 1, NUMSMD
DO 4
I = 1, NUMQ
A
A
DETERMINE ADVANCE CHARACTERISTICS
DETERMINE INFILTRATION CHARACTERISTICS
DETERMINE TIME TO INFILTRATE SOIL MOISTURE DEFICIENCY
DETERMINE PERFORMANCE PARAMETERS
WRITE MODEL OUTPUT
END LOOP
4
END LOOP
3
END LOOP
2
END LOOP
1
END

Figure 19. Simplified flowchart for Program FURSIM (from Binder, 1981).

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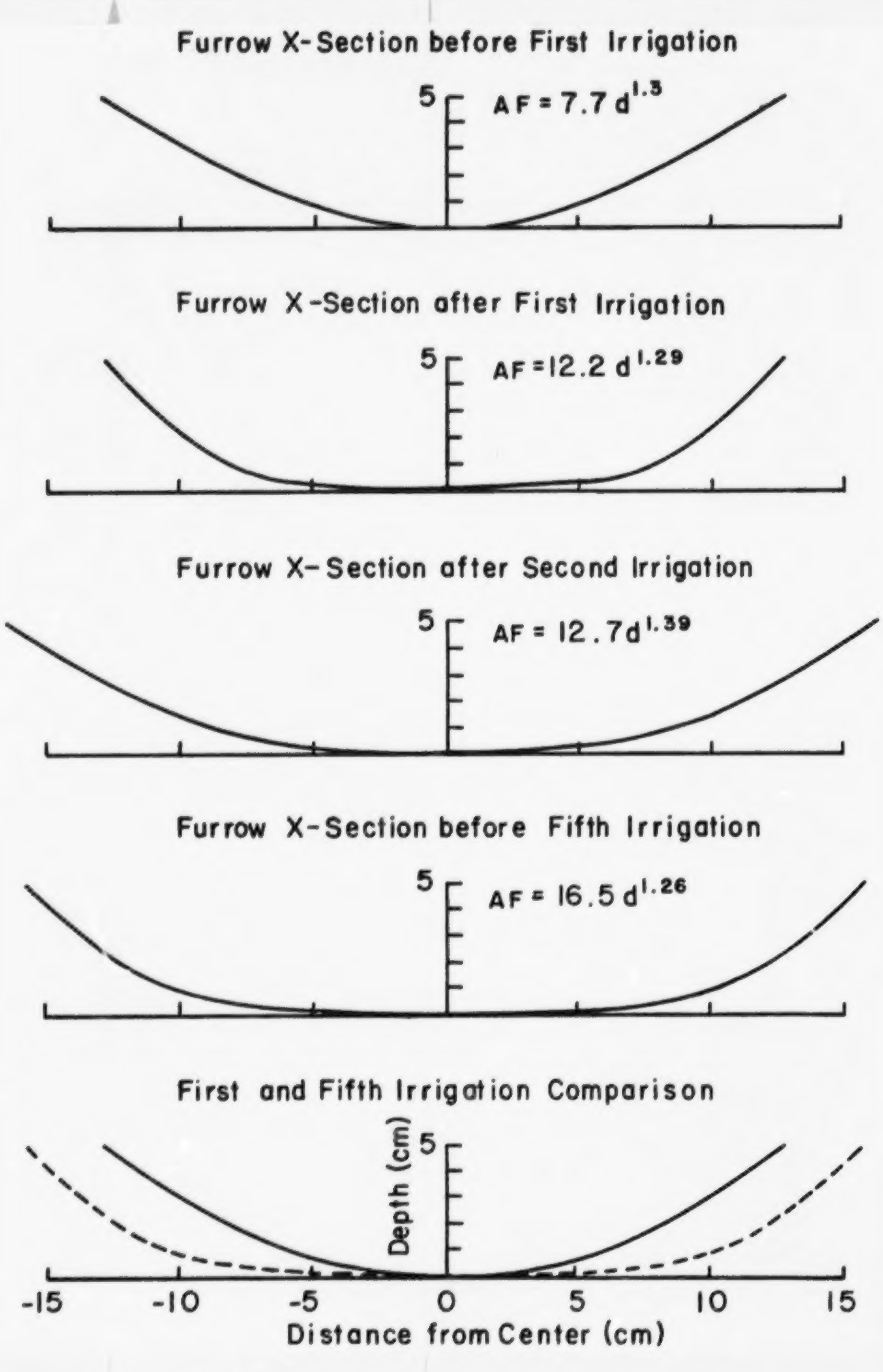

Figure 20. Illustration of seasonal change in furrow cross-section (after Salazar, 1977).

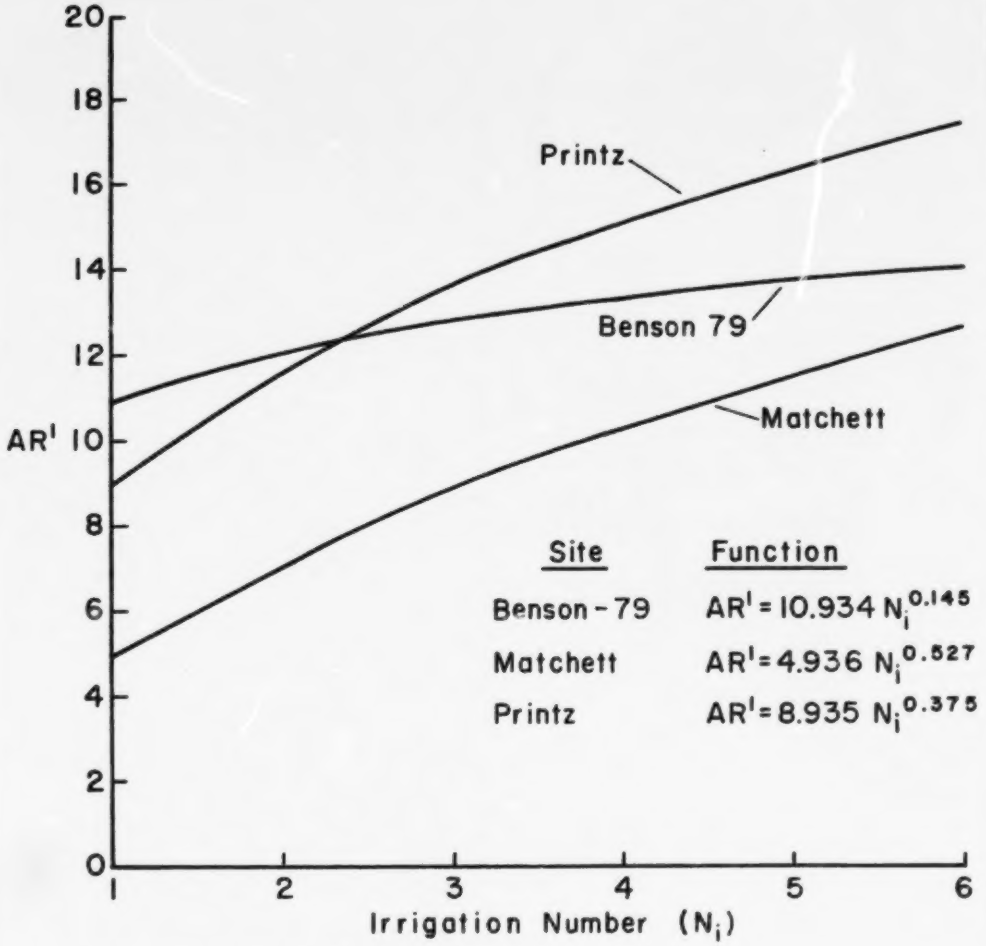

Figure 21. Adjusted AR function (AR') for the three field sites (from Binder, 1981).

Soil Moisture

The surface soil moisture content influences the furrow advance flow and infiltration characteristics. An empirical relationship for the surface soil moisture content as a function of total soil moisture deficit was determined. The relationship is of the form:

$$\theta = \theta c1 - \theta c2\ (SMD) \tag{39}$$

where,

θ = surface soil moisture content on a volumetric basis (%),

$\theta c1$, $\theta c2$ = empirical coefficients, and

SMD = total soil moisture deficit (mm).

The surface soil moisture content function for the Benson-79 and Printz sites are shown in Figure 22. A relationship for the Matchett site could not be developed due to an insufficient amount of field data.

Furrow Advance

The furrow advance flow has been determined to be a function of the furrow discharge, the soil surface moisture content, and the furrow wetted perimeter. The furrow discharge and wetted perimeter are defined at the head of the furrow. The soil surface moisture content is an average value over the entire furrow. A stepwise multiple regression has been performed resulting in relationships describing the advance characteristics having the following form:

$$r = rc1\, p^{rc2} Q^{rc3} \theta^{rc4} WP^{rc5} \tag{40}$$

$$p = pc1\, r^{pc2} Q^{pc3} \theta^{pc4} WP^{pc5} \tag{41}$$

where,

r = exponent in Equation 8,

rc1, rc2, rc3, rc4, rc5 = empirical coefficients,

p = coefficient in Equation 8,

pc1, pc2, pc3, pc4, pc5 = empirical coefficients.

Equations 40 and 41 are solved simultaneously in the model. The empirical coefficients relating p and r for the three sites are given in Table 9. The level of significance for each independent variable in Equations 40 and 41 is shown in Table 10. The level of significance is determined based on when each independent variable is entered in the stepwise regression. The most significant variable is entered first in the stepwise regression analysis.

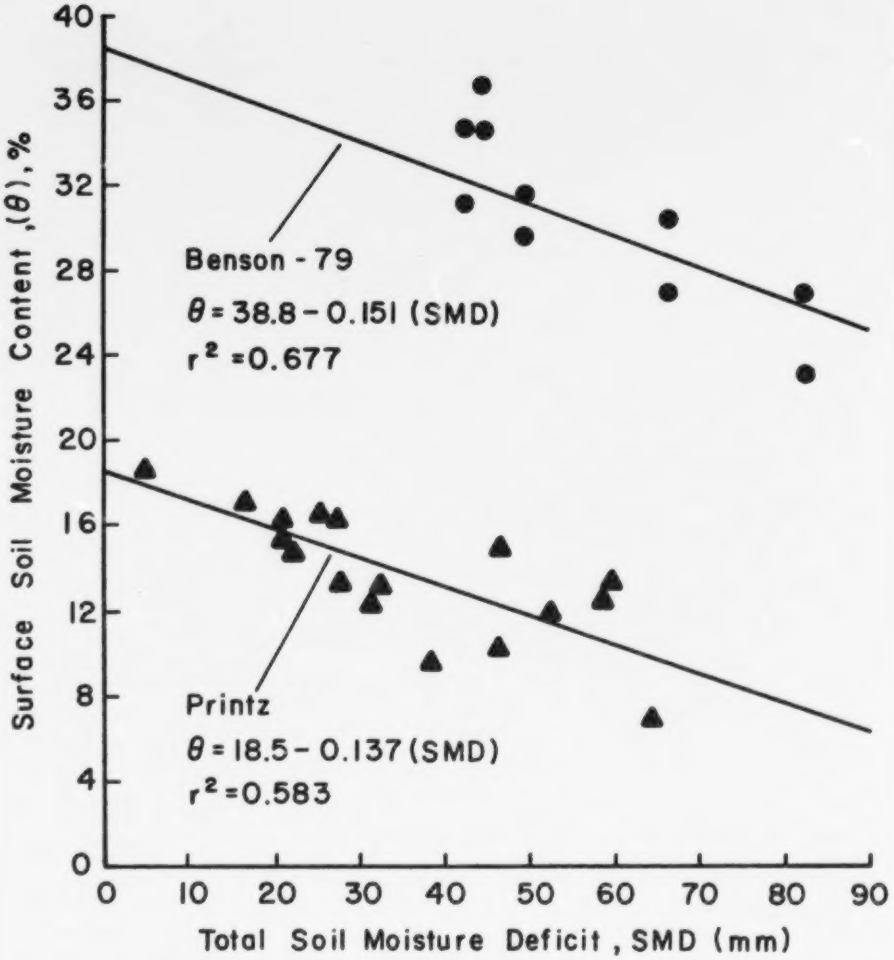

Figure 22. Surface soil moisture content functions for the Benson-79 and Printz sites (from Binder, 1981).

TABLE 9. p AND r FUNCTION COEFFICIENTS FOR THE THREE FIELD SITES (FROM BINDER, 1981).

Site	rc1	rc2	rc3	rc4	rc5	r^2 [1]
Benson-79	0.0865924	-0.2476	0.1763	0.5485	0.2151	0.73599
Matchett	0.9145371	-0.2973	0.1936	0.0	0.1763	0.89979
Printz	0.5174722	-0.4283	0.3213	0.2616	0.1089	0.93859

Site	pc1	pc2	pc3	pc4	pc5	r^2
Benson-79	0.0000810	-2.7264	0.5763	2.4624	0.6350	0.80412
Matchett	1.0077796	-2.9972	0.6787	0.0	0.5395	0.91076
Printz	0.3774947	-2.1325	0.7005	0.5452	0.1853	0.91839

[1] Coefficient of determination.

TABLE 10. LEVEL OF SIGNIFICANCE OF INDEPENDENT VARIABLES IN THE p AND r FUNCTIONS (BINDER, 1981).

		Level of Significance			
Site	Function	1	2	3	4
Benson-79	r	p	Q	θ	WP
Matchett	r	p	Q	WP	--
Printz	r	p	θ	Q	WP
Benson-79	p	r	θ	Q	WP
Matchett	p	r	Q	WP	--
Printz	p	r	θ	Q	WP

Infiltration

The model employs the modified Kostiakov equation for describing infiltration (Eq. 7). The basic intake rate was determined using the Fibonacci search enhanced volume balance technique developed by Ley (1978) which is equivalent to the approach Neff (1981) used as described earlier. The optimization technique selects the c' value that minimizes the error between measured and predicted runoff. The basic intake rate expressed as the coefficient c in Equation 7 has been shown to be considered constant from irrigation to irrigation through the season (Elliott and Walker, 1980) but has been found to be linearly related to the furrow discharge. The resulting c' function is of the form:

$$c' = CC1(Q) + CC2 \qquad (42)$$

where,

CC1, CC2 = empirical coefficients.

Figures 23, 24 and 25 show the c' functions for the three field sites. Once the c' value is determined using Equation 42, the model uses the volume balance technique described by Christiansen et al. (1966) for determining the a' coefficient and b' exponent in Equation 7.

The volume of infiltration is determined using the appropriate equations in Section IV. Inspection of these equations reveal that the infiltrated volume is determined at the time of cutoff. However, there remains a volume of water in surface storage that will partially infiltrate but was ignored in the earlier analyses. The fraction of surface storage at the time of cutoff that infiltrates (f) has been found to be related to soil type. There appears to be no strong relationship for this f value as a function of irrigation number. The f values for the Benson-79, Matchett and Printz sites are 0.50, 0.60, and 0.85, respectively. These values indicate that the f value increases for a lighter textured soil.

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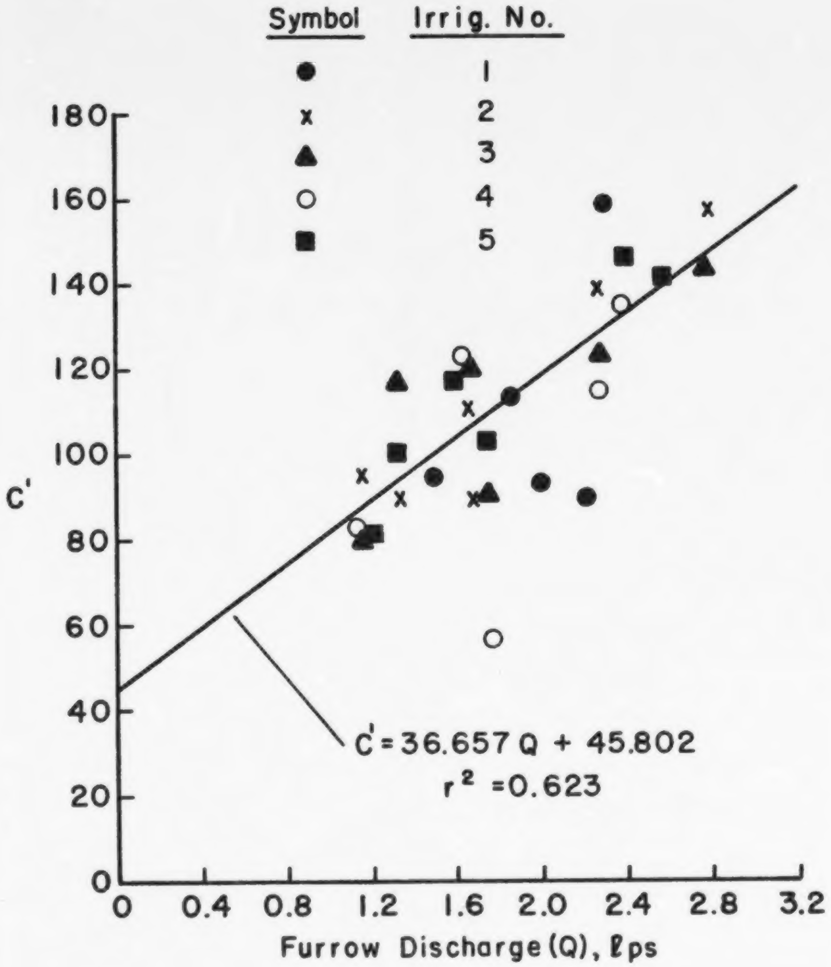

Figure 23. c'-function for the Benson-79 site (from Binder, 1981).

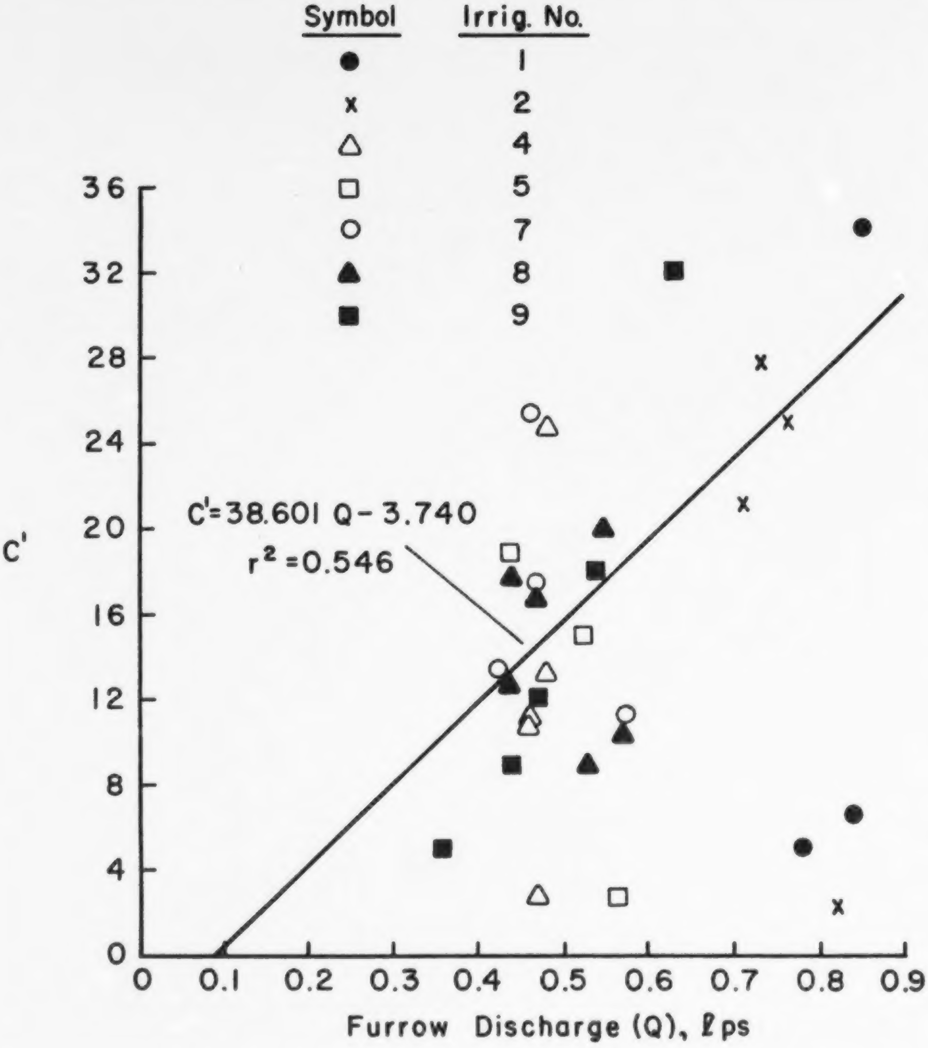

Figure 24. c'-function for the Matchett site (from Binder, 1981).

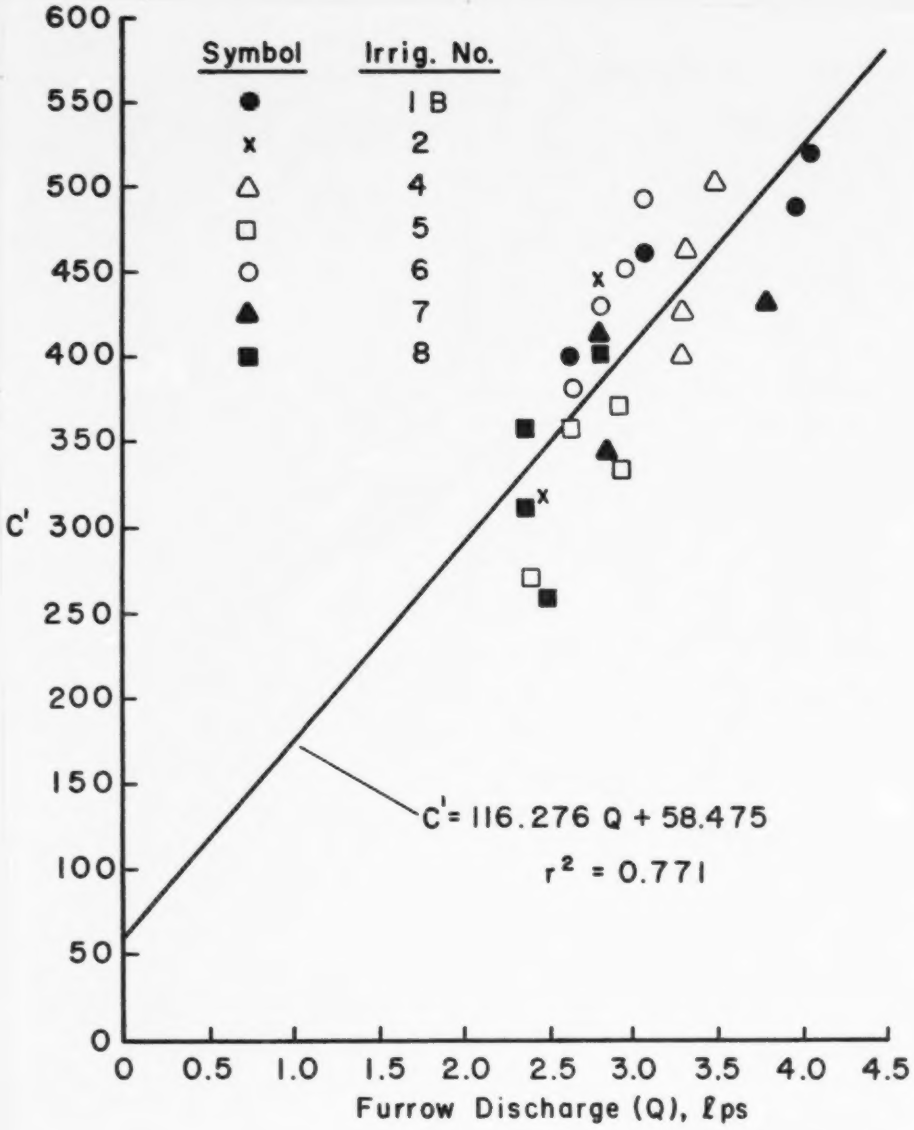

Figure 25. c'-function for the Printz site (from Binder, 1981).

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Data Requirements

The data requirements of the model consist of two main subject areas. The first subject area concerns the data required to determine the model input function coefficients. The second subject area pertains to the actual model input data.

Data required for determining the model input function coefficients are:

1. Average furrow inflow rate;
2. Volume of runoff;
3. Time of cutoff;
4. Time of advance to end of furrow;
5. Coefficients in power advance function;
6. Furrow spacing;
7. Average furrow slope;
8. Length of furrow;
9. Basic intake rate;
10. Volumetric surface soil moisture content;
11. Soil moisture deficiency; and
12. Coefficients in the parabolic furrow cross-section equation.

The input data required for Program FURSIM to operate in the production mode are:

1. Furrow spacing, slope and length;
2. Estimate of Manning's roughness coefficient (suggested value is 0.02);
3. Estimate of fraction of surface storage at time of cutoff that will infiltrate;
4. Coefficients for determining volumetric surface soil moisture content as a function of soil moisture deficiency;
5. Coefficients for determining basic intake rate as a function of furrow inflow rate;
6. Exponent in parabolic furrow cross-section equation determined for the first irrigation of the season;
7. Coefficients for determining constant in parabolic furrow cross-section data as a function of irrigation number;
8. Coefficients in p-function;
9. Coefficients in r-function; and
10. Desired decision variable loop limits and iteration increment values.

MODEL PERFORMANCE

The objective in developing Program FURSIM was to minimize the error between measured and predicted performance parameters. Two fundamental quantities have been chosen for determining how well this objective was achieved--the advance time to the end of the field (TEND) and the total volume of runoff (VRO). Accurate prediction of these two variables represents how well the temporal and spatial infiltration properties have been characterized. Once

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the infiltration properties are known, system performance as a function of the decision and state variables can easily be determined.

The model evaluation process was undertaken in two stages. The first stage consisted of testing the model's ability to describe parameter interactions using the three individual data sets--Benson-79, Matchett and Printz. The second stage involved using the Benson-79 calibrated model for predicting performance during the 1977 season at the same site. Figures 26 through 33 illustrate how well the modeling procedure could be calibrated using the relations found in Equations 38 through 42. Ideally, all data should lie on the 45° line and if variability is present there should be an equal number of data points above and below the line at approximately the same total deviation. The model is considered adequate in describing the conditions for which it was calibrated if the magnitude of the total deviation is within acceptable limits.

Two measures of model performance have been chosen to mathematically characterize the data scatter in Figures 26 through 33. The first measure, average calibration error, is defined as:

$$AVE = \frac{\sum_{i=1}^{j} (PREi - MEAi)}{j} \tag{43}$$

where,

AVE = average calibration error, min or m^3,

$PREi$ = individual predicted value, min or m^3,

$MEAi$ = individual measured value, min or m^3, and

j = total sample number.

The average calibration error represents how well the 45° line "splits" the plotted values or how well the model prediction curve falls between the measured values.

The second measure, average model accuracy, is defined as:

$$AMA = \frac{\sum_{i=1}^{j} |PREi - MEAi|}{j} \tag{44}$$

where,

AMA = average model accuracy, min or m^3.

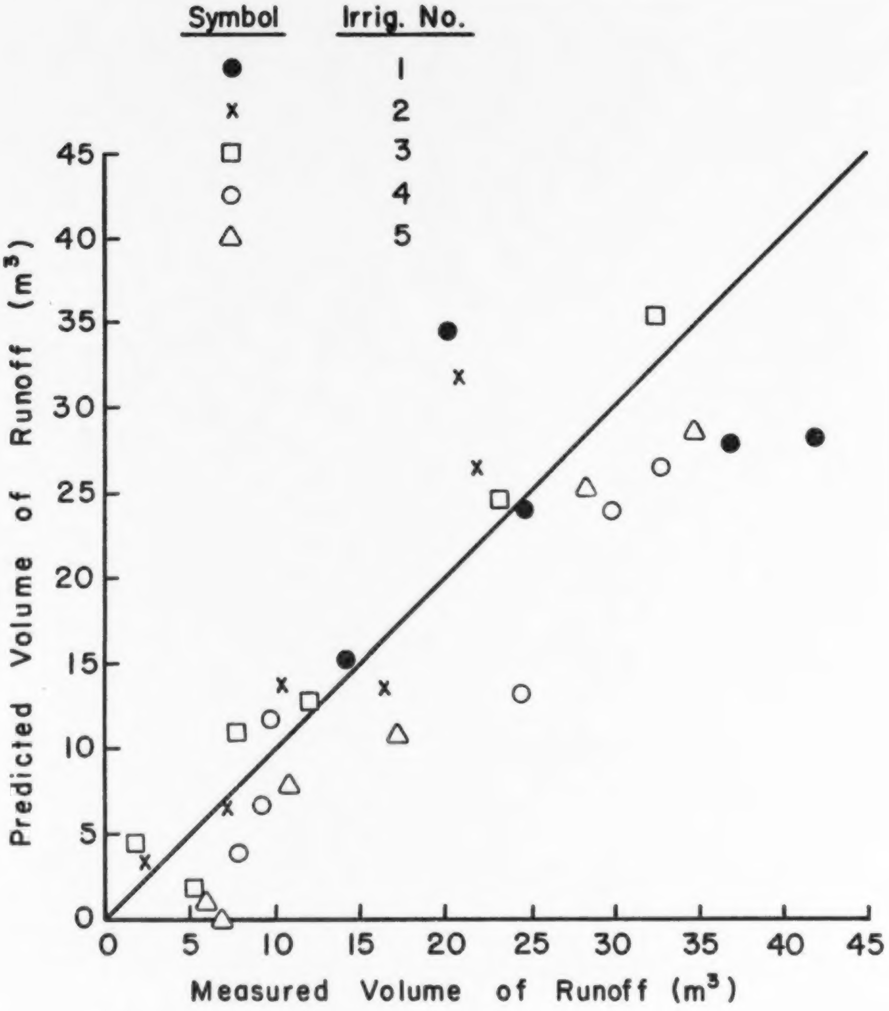

Figure 26. Comparison of predicted and measured runoff volumes for the Benson-79 site (from Binder, 1981).

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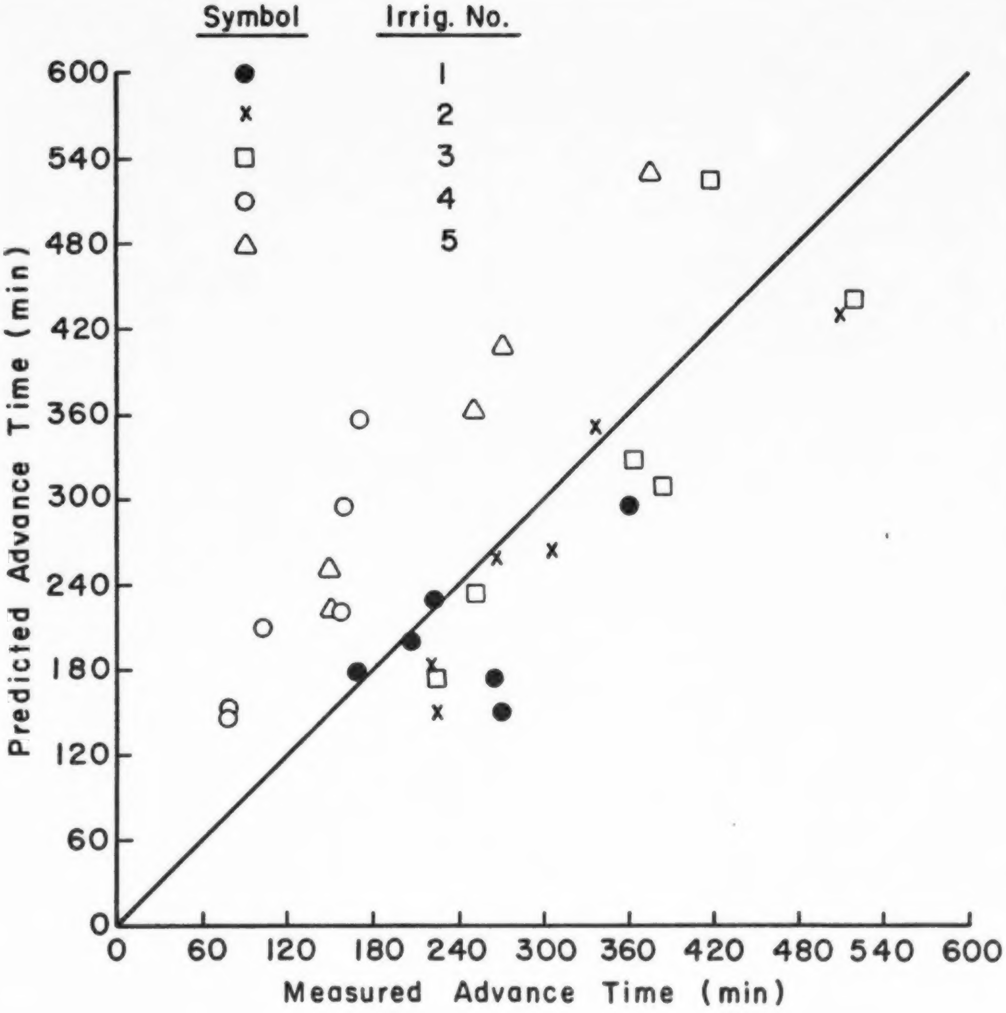

Figure 27. Comparison of predicted and measured advance times for the Benson-79 site (from Binder, 1981).

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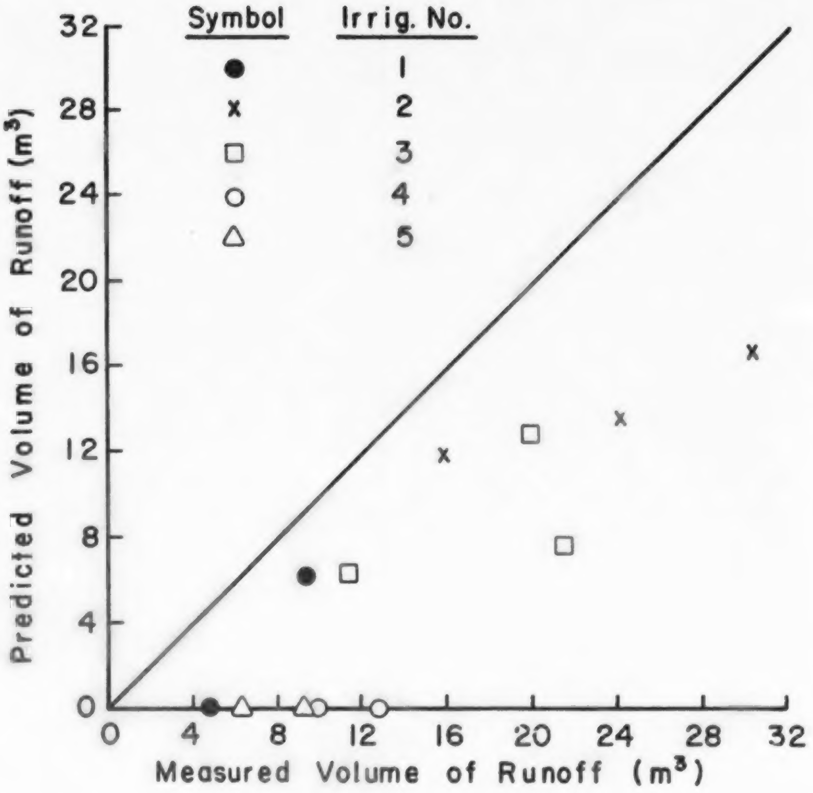

Figure 28. Comparison of predicted and measured runoff volumes for the Benson-77 site (from Binder, 1981).

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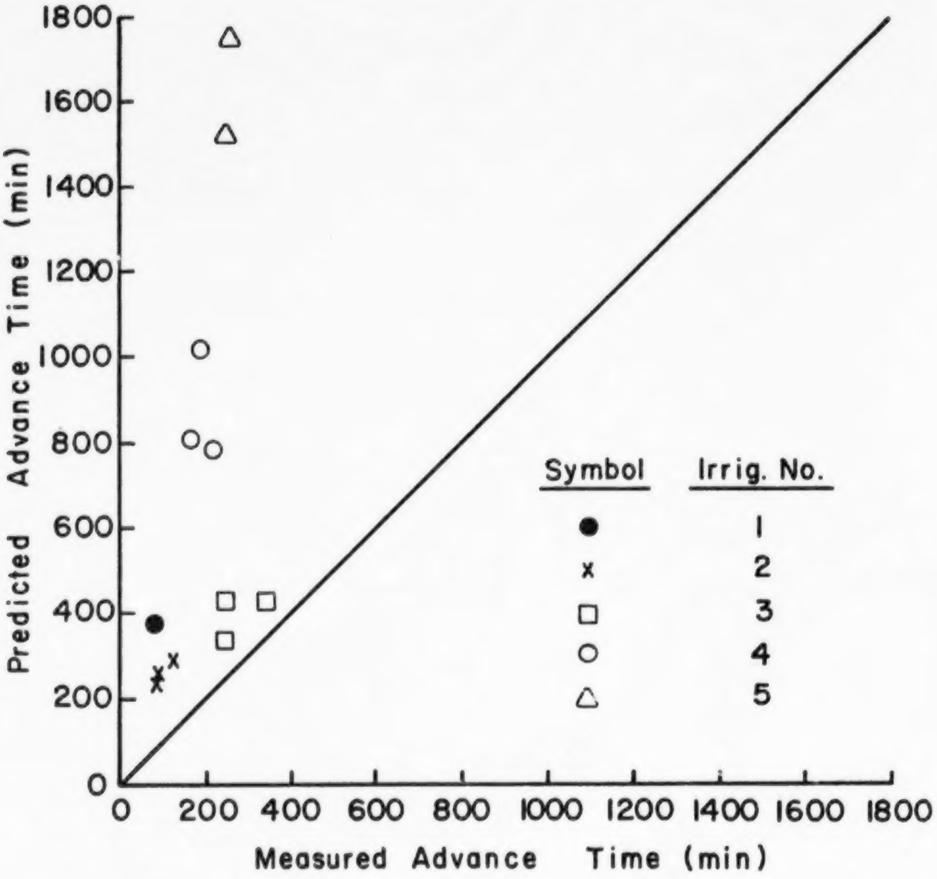

Figure 29. Comparison of predicted and measured advance times for the Benson-77 site (from Binder, 1981).

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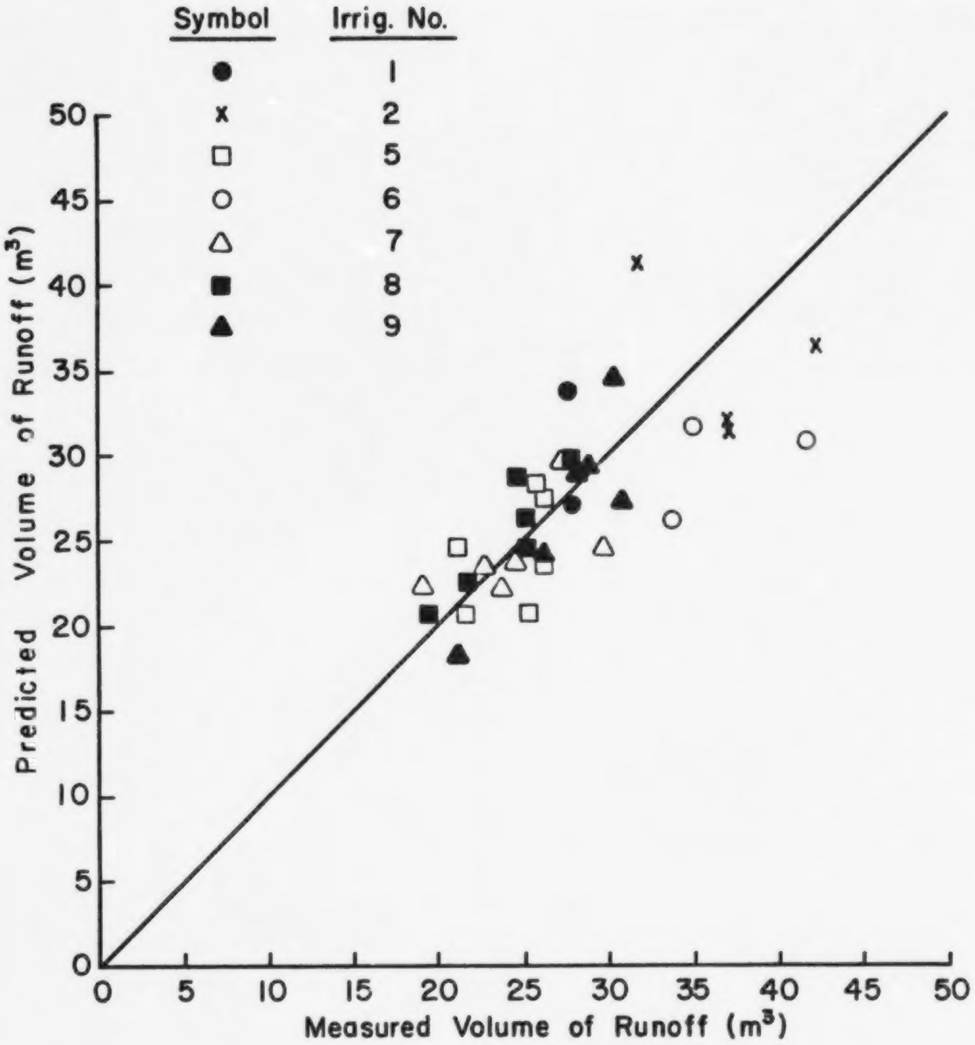

Figure 30. Comparison of predicted and measured runoff volumes for the Matchett site (from Binder, 1981).

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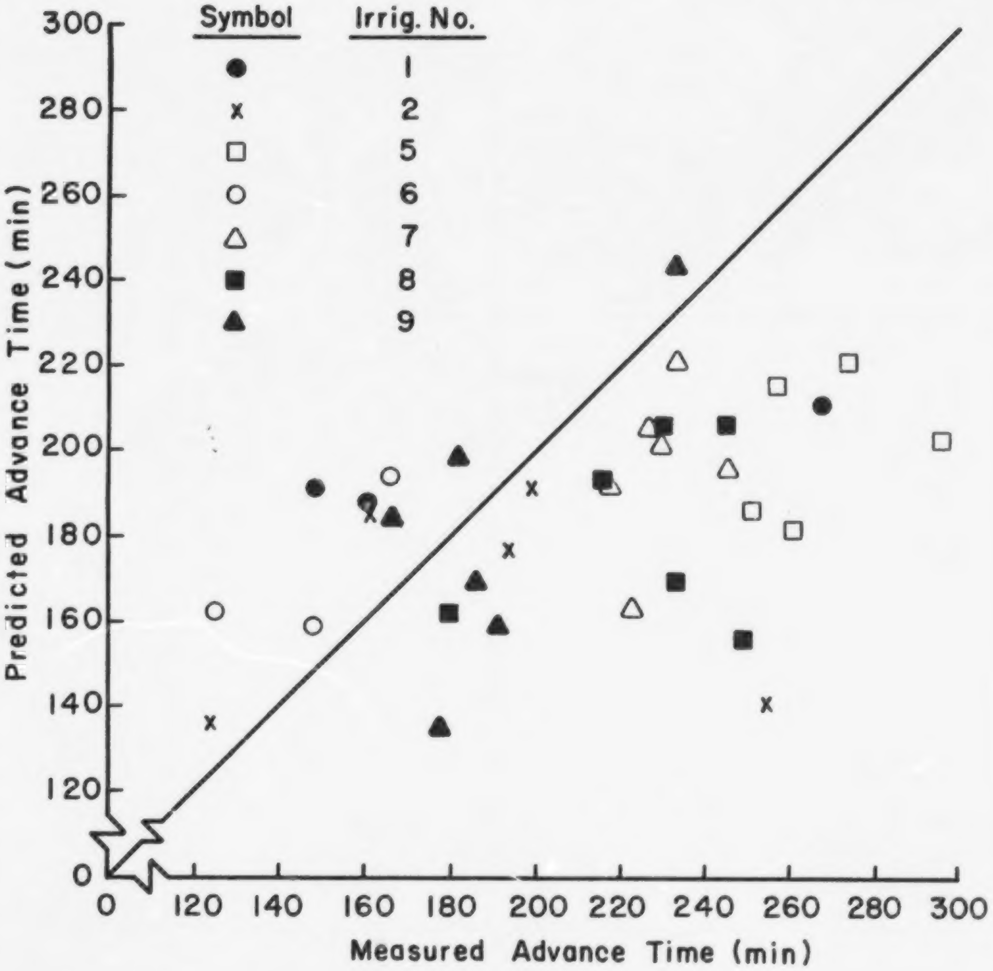

Figure 31. Comparison of predicted and measured advance times for the Matchett site (from Binder, 1981).

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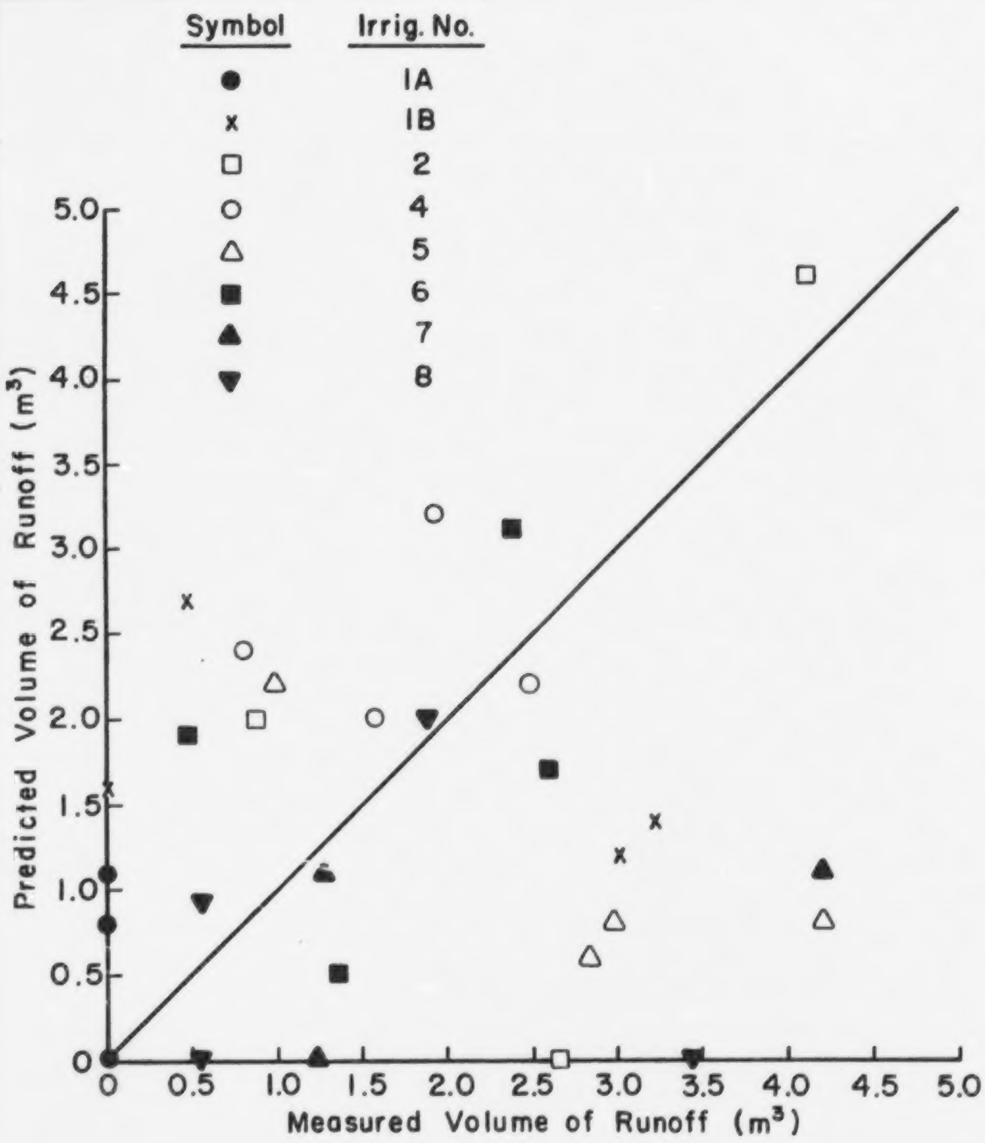

Figure 32. Comparison of predicted and measured runoff volumes for the Printz site (from Binder, 1981).

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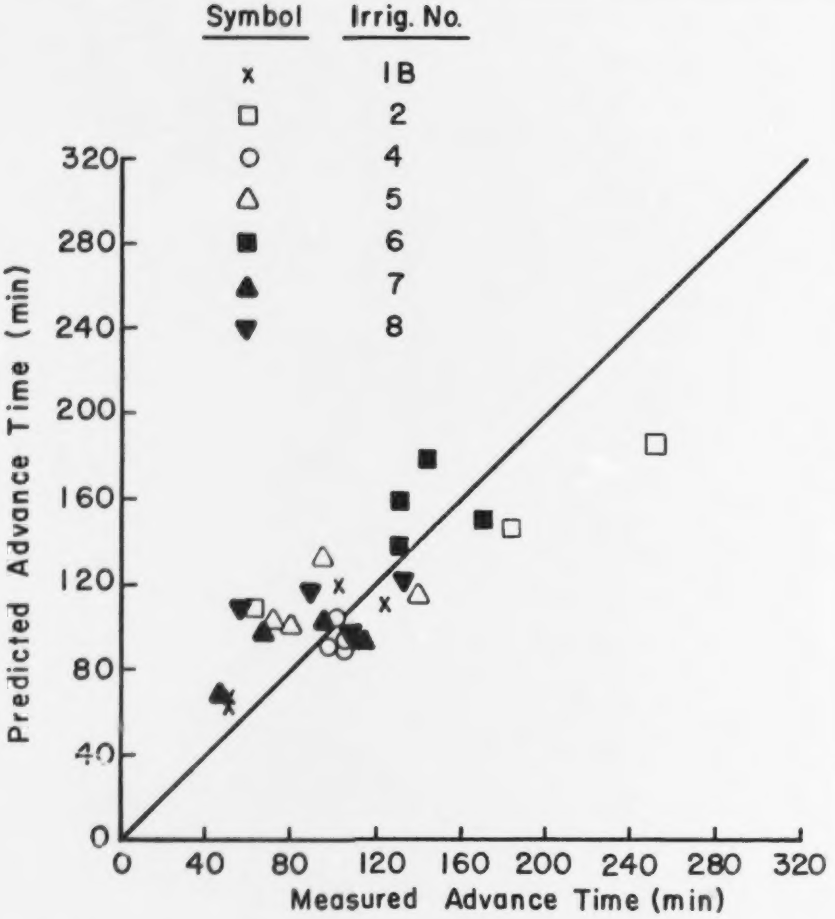

Figure 33. Comparison of predicted and measured advance times for the Printz site (from Binder, 1981).

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The average model accuracy represents the average error (plus or minus) that could be expected in predicting the two fundamental quantities with no associated confidence.

The results of the analysis are shown in Table 11. Inspection of the calibration error for the Benson-79, Matchett, and Printz sites shows that the model does a good job of predicting within the range of the measured values. The Benson-77 values indicate the Benson-79 calibration over-predicted the advance and under-predicted the runoff (both by a wide margin). Inspection of the model accuracy reveals that the model does a reasonably good job of prediction for the individually calibrated sites; however, the Benson-77 prediction error is significantly higher. Thus, it can be concluded that until the data basis is sufficient to describe not only irrigation-to-irrigation changes in infiltration rates, but also year to year changes, the model must be limited to applications where it has been calibrated.

IMPROVING FURROW IRRIGATION PERFORMANCE

Furrow irrigation performance can be improved through management decisions if the factors controlling existing performance are correctly identified. The specific performance parameter and level of performance under consideration depends on the objectives of the system operation. Management decisions that directly influence performance include furrow discharge rate, time of cutoff, and the soil moisture deficit at the time of irrigation. The irrigation number (or number of previous irrigations) can also be regarded as a decision variable. However, in many cases the number of irrigations for a season may not be as controllable as the other decision variables.

Program FURSIM can be used as a tool for making the proper management decisions that will result in the desired system performance. Table 12 is an example printout from Program FURSIM which shows the state variables and system performance as a function of the decision variables.

The example given is for the Benson-79 site, irrigation number 1, a cutoff time of 600 min, and a soil moisture deficit of 55.5 mm. The user can determine the values for the state variables and performance parameters for any furrow discharge over the range of 1 to 3 lps. The performance parameter having the most significance depends on the specific goals of the improvement program. For example, if the objective is to minimize deep percolation while maintaining an application efficiency of 70 percent, then a furrow discharge of 1.9 lps should be chosen.

The form of the computer output shown in Table 12 can be cumbersome from a system managers viewpoint for simulating irrigations on a seasonal basis. For example, simulating the irrigation season at the Benson-79 site for five irrigations, a range of cutoff times from 480 - 720 min (30 min increments), and a furrow discharge range of 1 - 3 lps (0.1 lps increments) resulted in 135 pages of computer output.

When this type of problem arose in the work of Salazar (1977), the first writer suggested a simple two dimensional search routine be added to the model. The result was a very successful method of establishing the

TABLE 11. CALIBRATION ERROR AND MODEL ACCURACY OF PROGRAM FURSIM (FROM BINDER, 1981).

	VERIFICATION ERROR				MODEL ACCURACY			
	TEND (min)		VRD (m^3)		TEND (min)		VRO (m^3)	
Site	$\overline{X}$	S	$\overline{X}$	S	$\overline{X}$	S	$\overline{X}$	S
Benson (1979)	28.33	98.53	-1.49	5.95	81.42	60.14	4.69	3.86
Benson (1977)	495.12	480.34	-8.46	3.80	495.12	480.34	8.46	3.80
Matchett	-23.98	41.31	-0.93	6.11	39.42	26.41	4.17	3.94
Printz	4.95	27.46	-0.34	1.60	23.28	14.72	1.29	0.98

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TABLE 12. EXAMPLE PROGRAM FURSIM PRINTOUT SHOWING STATE VARIABLES AND SYSTEM PERFORMANCE AS A FUNCTION OF THE DECISION VARIABLES (FROM BINDER, 1981).

FARM:HENSON-79 IRRIG. NO.: 1 TCO(MIN): 600.0 SMD(MM): 55.5

Q (LPS)	a'	b'	c'	p	r	TSMD (MIN)	TEND (MIN)	$\overline{A}$ (CM**2)	E_a	TWR	DPR
1.00	27577.2	.000	82.5	8.87	.661	690.7	621.7	34.64	1.000	0.000	0.000
1.10	27165.1	0.000	86.1	9.15	.671	666.1	543.5	37.00	.969	.032	0.000
1.20	26781.2	.000	89.8	9.42	.679	643.0	481.7	39.29	.934	.066	0.000
1.30	26425.4	0.000	93.5	9.67	.687	622.0	431.9	41.53	.902	.098	0.000
1.40	26095.9	.000	97.1	9.91	.694	601.9	390.9	43.71	.872	.128	0.000
1.50	25790.7	0.000	100.8	10.14	.701	583.2	356.8	45.85	.842	.155	.004
1.60	25475.5	.000	104.5	10.35	.708	564.8	327.9	47.94	.813	.179	.008
1.70	24798.7	.005	108.1	10.56	.714	545.3	303.2	50.00	.786	.199	.015
1.80	24274.3	.008	111.8	10.76	.720	528.7	291.8	52.01	.760	.217	.023
1.90	23865.0	.010	115.5	10.95	.726	512.6	263.2	53.99	.733	.235	.032
2.00	23544.2	.011	119.1	11.14	.731	498.1	246.9	55.95	.709	.251	.041
2.10	23292.7	.012	122.8	11.32	.736	483.9	232.4	57.97	.693	.267	.051
2.20	23096.3	.012	126.4	11.49	.741	470.9	219.5	59.76	.558	.281	.061
2.30	22944.3	.012	130.1	11.66	.746	459.1	208.0	61.52	.634	.296	.071
2.40	22828.4	.012	133.8	11.83	.751	448.3	197.6	63.46	.611	.307	.082
2.50	22742.2	.011	137.4	11.99	.755	437.4	188.1	65.28	.589	.319	.093
2.60	22680.7	.010	141.1	12.14	.759	427.4	179.6	67.08	.565	.336	.104
2.70	22639.8	.009	144.8	12.29	.763	418.2	171.8	68.95	.544	.341	.115
2.80	22616.2	.009	148.4	12.44	.767	409.8	164.6	70.61	.524	.351	.125
2.90	22607.3	.006	152.1	12.59	.771	401.1	158.1	72.34	.505	.360	.133
3.00	22610.9	.004	155.8	12.73	.775	393.0	152.0	74.06	.489	.369	.141

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infiltration coefficients from rate of advance and runoff data. The same procedure could also be applied to the model FURSIM, but was not thought of in time to be included in this project. Instead, Binder (1981) reduced the problem to be a short computational procedure and several graphical inputs. The interested reader may wish to contact one of the writers for these materials.

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APPENDIX A

FURROW EVALUATION DATA SUMMARY
(from Neff, 1981)

TABLE 13. SOIL TEXTURE DATA FOR THE BENSON FARM (1979).

GROUP 1			GROUP 2		
Station (meters)	Depth (cm)	Texture	Station (meters)	Depth (cm)	Texture
100	0-15	CL	100	0-15	C
	15-30	CL		15-30	C
	30-60	CL		30-60	C
	60-90	CL		60-90	CL
	90-120	CL		90-120	SCL
300	0-15	CL	300	0-15	C
	15-30	CL		15-30	C
	30-60	CL		30-60	C
	60-90	CL		60-90	CL
	90-120	L		90-120	CL
500	0-15	CL	500	0-15	CL
	15-30	CL		15-30	CL
	30-60	CL		30-60	SCL
	60-90	SCL		60-90	SCL
	90-120	SCL		90-120	CL

Key:

C = clay
CL = clay loam
L = loam
SCL = sandy clay loam

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TABLE 14. SOIL TEXTURE DATA FOR THE MATCHETT FARM.

GROUP 1			GROUP 2		
Station (meters)	Depth (cm)	Texture	Station (meters)	Depth (cm)	Texture
50	0-15	L	50	0-15	L
	15-30	SL		15-30	L
	30-60	C		30-60	CL
	60-90	SiC		60-90	CL
	90-120	CL		90-120	CL-L
200	0-15	CL	200	0-15	L
	15-30	CL		15-30	L
	30-60	SiL		30-60	SiCL
	60-90	CL		60-90	SiCL
	90-120	CL		90-120	SCL-SL
350	0-15	SiC	350	0-15	CL
	15-30	SiC		15-30	SiC-SiCL
	30-60	CL		30-60	L
	60-90	CL		60-90	CL
	90-120	SiCL		90-120	L

GROUP 3			GROUP 4		
Station (meters)	Depth (cm)	Texture	Station (meters)	Depth (cm)	Texture
50	0-15	L	100	0-15	L
	15-30	CL-L		15-30	L
	30-60	L		30-60	CL
	60-90	L		60-90	L
	90-120	SCL-SL		90-120	L
200	0-15	CL	200	0-15	L
	15-30	L		15-30	L
	30-60	CL		30-60	L
	60-90	CL		60-90	CL-L
	90-120	L		90-120	CL
350	0-15	CL-L	350	0-15	CL
	15-30	L		15-30	CL
	30-60	L		30-60	L
	60-90	CL		60-90	L
	90-120	CL-L		90-120	L

TABLE 14. (continued)

Key:

C = clay
CL = clay loam
L = loam
SCL = sandy clay loam
SL = sandy loam
SiC = silty clay
SiL = silt loam
SiCL = silty clay loam

TABLE 15. SOIL TEXTURE DATA FOR THE PRINTZ FARM.

GROUP 1			GROUP 2		
Station (meters)	Depth (cm)	Texture	Station (meters)	Depth (cm)	Texture
75	0-15	LS	75	0-15	S
	15-30	SL		15-30	LS
	30-60	SL		30-60	SL
	60-90	SL		60-90	LS
	90-120	SL		90-120	S
175	0-15	S	175	0-15	LS
	15-30	LS		15-30	SL
	30-60	SL		30-60	SL
	60-90	SL		60-90	SCL
	90-120	LS		90-120	SCL
275	0-15	S	275	0-15	LS
	15-30	SL		15-30	LS
	30-60	SL		30-60	SL
	60-90	SL		60-90	SCL
	90-120	LS		90-120	SCL

Key:

LS = loamy sand
S = sand
SCL = sandy clay loam
SL = sandy loam

TABLE 16. DATA SUMMARY FOR THE BENSON FARM (1979).

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m^3)	Total Inflow Volume (m^3)	Runoff Volume at time of cutoff (m^3)
1	1	1	42.5	220.5	690.0	43.0	1.855	1.964	24.544	81.306	23.118
		3		261.0	690.0	44.5	2.317	2.391	36.289	98.969	18.721
		5		268.5	690.0	45.0	2.776	2.744	44.721	113.616	11.916
	2	1	42.5	360.5	721.5	39.0	1.508	1.596	32.622	69.071	13.252
		3		205.0	718.5	43.5	2.009	2.127	24.713	91.694	35.233
		5		177.5	719.0	42.0	2.211	2.154	23.551	92.902	40.207
2	1	1	49.2	258.5	599.0	42.0	1.683	1.667	26.102	59.923	15.452
		3		217.0	600.0	36.0	2.794	2.525	36.384	90.906	19.557
		5		216.0	602.5	39.5	2.262	2.284	29.320	82.556	20.463
	2	1	49.2	512.5	613.5	46.0	1.135	1.128	34.895	41.537	1.917
		3		337.0	614.5	45.5	1.322	1.323	26.725	48.761	6.453
		5		305.0	615.0	40.5	1.647	1.676	30.142	61.855	9.679
3	1	1	66.9	379.5	590.0	48.0	1.738	1.748	39.566	61.884	10.870
		3		217.0	589.0	52.0	2.760	2.821	35.930	99.704	30.234
		5		245.5	589.5	46.0	2.256	2.325	33.235	82.235	21.885
	2	1	66.9	414.0	607.5	59.0	1.158	1.159	28.754	42.260	4.640
		3		519.5	610.5	52.0	1.317	1.316	41.043	48.197	1.395
		5		361.0	608.0	51.0	1.663	1.673	36.028	61.015	6.827
4	1	1	44.4	104.5	516.0	50.0	1.754	1.788	10.999	55.359	22.742
		3		74.0	519.0	51.0	2.370	2.532	10.523	78.843	30.849
		5		72.5	517.0	51.0	2.279	2.382	9.912	73.904	27.904
	2	1	44.4	168.5	480.0	61.0	1.135	1.201	11.477	34.578	6.982
		3		163.0	480.5	61.0	1.330	1.388	13.008	40.021	8.274
		5		154.0	483.0	59.0	1.644	1.691	15.191	49.018	8.802
5	1	1	82.6	253.0	606.5	52.0	1.728	1.785	26.235	64.964	15.752
		3		145.0	606.0	52.0	2.585	2.628	22.493	95.563	32.981
		5		146.5	604.5	55.0	2.384	2.455	20.959	89.054	26.587
	2	1	82.6	355.0	619.0	63.0	1.168	1.171	24.884	43.480	6.087
		3		369.0	618.0	62.0	1.314	1.332	29.097	49.382	5.127
		5		267.5	618.0	60.0	1.590	1.637	25.511	60.686	9.770

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TABLE 17. DATA SUMMARY FOR THE MATCHETT FARM.

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m^3)	Total Inflow Volume (m^3)	Runoff Volume at time of cutoff (m^3)
1	4	1	15.6	267.0	1385.5	34.0	0.779	0.631	12.486	52.470	15.252
		3		149.0	1479.5	30.5	0.842	0.630	7.526	55.896	27.560
		5		160.8	1478.5	31.0	0.847	0.736	8.173	65.321	27.179
2	1	1	31.4	242.8	1375.0	43.5	0.685	0.690	9.985	56.926	31.730
		3		240.2	1445.2	35.6	0.731	0.724	10.538	62.783	34.164
		5		527.0	1447.8	32.4	0.797	0.802	25.200	69.675	22.682
	2	1	29.2	195.8	1315.5	41.0	0.728	0.793	8.549	62.630	43.058
		5		212.5	1312.0	41.3	0.751	0.801	9.581	63.083	34.374
	3	1	31.6	194.8	1288.8	36.0	0.756	0.827	8.837	63.986	41.306
		3		108.8	1368.8	36.4	0.818	0.854	5.342	70.163	55.724
		5		255.5	1364.5	33.0	0.916	0.888	14.043	72.725	31.264
	4	1	25.6	160.2	1316.2	38.3	0.739	0.749	7.021	59.179	36.409
		3		198.8	1341.8	36.4	0.708	0.714	8.447	57.482	36.460
		5		124.0	1340.5	37.7	0.935	1.025	6.956	82.406	58.186
3	1	1	25.5	183.0	1393.2	44.0	0.755	0.776	8.397	64.889	38.038
		3		162.0	1393.2	41.6	0.829	0.845	8.056	70.626	38.957
		5		278.5	1393.5	40.3	0.665	0.673	11.107	56.265	22.055
	2	1	23.4	362.5	1424.2	35.0	0.728	0.736	15.839	62.914	27.124
		5		598.5	1420.8	31.0	0.651	0.663	23.373	56.536	15.386
4	1	1	52.4	341.5	1375.5	58.0	0.746	0.751	15.296	61.950	33.274
		3		315.5	1376.0	52.0	0.733	0.738	13.878	60.901	38.468
		5		356.5	1394.8	50.7	0.773	0.777	16.525	64.993	33.651
	3	1	25.8	222.5	1370.0	52.2	0.455	0.473	6.069	38.842	25.534
		3		225.5	1369.8	49.7	0.597	0.612	8.079	50.300	21.867
		5		208.2	1369.0	52.5	0.482	0.501	6.024	41.143	22.963
	4	1	21.2	217.2	1331.5	45.5	0.463	0.481	6.039	38.450	19.819
		3		193.2	1331.5	45.3	0.466	0.471	5.401	37.637	23.408
		5		183.5	1330.8	50.0	0.483	0.497	5.320	39.670	22.824
5	1	1	39.7	126.8	1277.2	67.8	0.789	0.803	6.004	61.568	46.071
		3		143.0	1267.2	63.6	0.622	0.632	5.336	48.033	28.655
		5		143.5	1278.2	54.0	0.881	0.909	7.586	69.676	43.435
	2	1	39.9	205.5	1416.2	53.6	0.646	0.653	7.966	55.474	33.248
		3		203.2	1472.2	39.3	0.846	0.870	10.316	76.862	38.407
		5		174.5	1482.2	51.0	0.741	0.751	7.761	66.764	38.044
	3	1	11.6	304.5	1381.8	57.0	0.443	0.480	8.097	39.787	20.960
		3		274.2	1381.5	60.0	0.481	0.484	7.906	40.129	24.375
		5		296.5	1381.0	47.8	0.519	0.522	9.226	43.257	20.640

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TABLE 17. (continued)

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m^3)	Total Inflow Volume (m^3)	Runoff Volume at time of cutoff (m^3)
5	4	1	17.8	257.8	1389.2	54.0	0.494	0.498	7.644	41.518	25.439
		3		260.2	1388.2	54.3	0.571	0.576	8.922	47.973	25.075
		5		251.0	1375.8	53.4	0.561	0.566	8.454	46.720	25.559
6	1	1	41.8	189.0	1405.0	64.2	0.649	0.705	7.361	59.398	43.263
		3		204.2	1402.5	54.3	0.597	0.628	7.310	52.822	31.733
		5		267.5	1402.0	52.5	0.645	0.669	10.354	56.301	31.091
	2	1	41.0	198.5	1420.5	60.0	0.630	0.669	7.498	56.989	35.422
		3		248.2	1407.0	41.8	0.791	0.886	11.780	74.801	31.861
		5		203.2	1416.5	55.0	0.607	0.702	7.402	59.703	33.468
	4	1	32.2	166.5	1395.5	53.7	0.513	0.536	5.124	44.870	33.046
		3		125.5	1395.0	64.2	0.602	0.613	4.531	51.300	40.662
		5		148.2	1394.5	58.5	0.612	0.631	5.442	52.777	34.031
7	1	1	62.4	269.0	1376.0	64.8	0.660	0.657	10.660	54.232	37.405
		3		230.8	1377.5	53.0	0.796	0.804	11.027	66.412	40.260
	2	1	65.7	241.2	1259.2	50.6	0.759	0.804	10.991	60.749	31.910
		3		326.0	1237.2	37.6	0.868	0.923	16.984	68.539	23.114
		5		277.5	1246.5	51.0	0.692	0.728	11.515	54.480	25.319
	3	1	40.6	233.0	1418.8	59.2	0.433	0.450	6.049	38.320	23.051
		3		229.0	1418.0	61.2	0.467	0.471	6.414	40.087	21.975
		5		226.8	1417.5	52.5	0.455	0.486	6.196	41.336	18.570
	4	1	40.7	217.2	1405.5	59.0	0.489	0.494	6.377	41.669	28.921
		3		223.0	1405.5	64.5	0.571	0.576	7.634	48.572	26.444
		5		245.8	1403.5	62.5	0.481	0.484	7.092	40.781	23.689
8	3	1	43.2	230.8	1463.5	59.3	0.437	0.434	6.049	38.075	21.246
		3		216.8	1463.5	59.3	0.467	0.471	6.069	41.376	24.560
		5		180.5	1463.8	51.0	0.547	0.554	5.927	48.661	27.215
	4	1	43.9	245.8	1346.2	58.0	0.440	0.444	6.496	35.877	18.964
		3		249.5	1346.0	63.0	0.567	0.575	8.488	46.449	23.875
		5		233.8	1345.2	59.3	0.529	0.537	7.420	43.363	24.535
9	3	1	54.5	233.8	1402.0	60.8	0.356	0.376	4.996	31.620	20.556
		3		182.2	1402.0	63.0	0.435	0.465	4.755	39.143	25.691
		5		166.8	1401.8	54.4	0.471	0.541	4.711	45.520	28.021
	4	1	54.0	178.0	1445.0	67.5	0.631	0.651	6.735	56.452	29.478
		3		186.2	1445.0	75.2	0.513	0.522	5.730	45.231	29.813
		5		191.2	1445.0	71.5	0.541	0.553	6.210	47.961	27.148

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TABLE 18. DATA SUMMARY FOR THE PRINTZ FARM.

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m³)	Total Inflow Volume (m³)	Runoff Volume at time of cutoff (m³)
1A	1	1	58.3	--	248.0	9.5	--	4.811	--	71.586	0.000
		3		--	250.0	10.0	--	3.525	--	52.877	0.000
		5		--	251.0	9.0	--	3.438	--	51.775	0.000
	2	1	64.3	--	242.0	7.5	--	2.437	--	35.384	0.000
		3		--	241.0	7.0	--	2.422	--	35.024	0.000
		5		--	242.0	4.0	--	3.273	--	47.530	0.000
1B	1	1	--	146.0	202.0	7.0	3.983	4.074	34.887	49.372	1.117
		3		52.0	101.0	19.0	3.958	3.749	12.348	22.718	2.531
		5		53.0	103.0	16.5	4.018	3.819	12.776	23.603	2.708
	2	1	--	104.0	178.0	11.0	2.628	2.768	16.400	29.557	0.015
		3		122.5	162.5	10.0	2.822	3.070	20.740	29.928	0.418
		5		111.0	161.0	10.0	3.471	3.489	23.114	33.703	0.793
2	1	1	31.4	92.5	109.0	19.5	4.955	4.996	27.503	32.676	0.737
		3		64.5	81.0	30.0	3.209	3.218	12.419	15.639	1.285
		5		39.0	57.0	23.5	5.740	5.702	13.431	19.500	1.052
	2	1	38.1	249.0	317.0	24.0	2.448	2.839	36.579	53.994	3.199
		3		184.0	218.0	24.0	2.818	2.919	31.113	38.186	0.579
		5		285.0	318.0	19.0	3.498	3.599	59.818	68.662	0.946
3	1	1	46.8	127.5	153.5	17.0	3.681	3.719	28.160	34.250	--
		3		79.5	119.5	23.0	3.260	3.385	15.550	24.269	--
		5		91.0	144.0	23.5	3.137	3.154	17.127	27.254	--
	2	1	46.8	71.5	110.5	16.0	3.515	3.672	15.081	24.347	1.123
		3		63.5	110.5	21.0	3.489	3.725	13.292	24.698	1.222
		5		107.5	143.5	22.0	4.268	4.456	27.526	38.363	0.367
4	1	1	32.6	274.0	293.0	17.0	3.795	3.843	62.398	67.559	0.026
		3		102.0	151.0	20.0	3.501	3.545	21.425	32.117	1.247
		5		106.5	163.0	9.0	3.346	3.433	21.379	33.570	1.726
	2	1	22.3	98.0	171.5	26.0	3.297	3.045	19.386	31.332	2.209
		3		105.0	173.0	24.0	3.286	3.119	20.704	32.378	0.671
		5		111.0	171.0	20.5	3.845	3.800	25.607	38.989	1.321
5	1	1	27.3	98.0	139.0	22.0	3.948	3.877	23.216	32.333	0.258
		3		71.0	138.5	30.5	2.932	2.841	12.489	23.609	3.326
		5		79.5	141.5	25.0	2.982	2.746	14.223	23.317	2.328
	2	1	21.5	94.0	171.0	19.5	2.397	2.396	13.516	24.586	2.578
		3		137.5	194.5	16.5	2.627	2.671	21.672	31.168	0.825
		5		142.5	194.0	15.0	3.097	3.096	26.476	36.036	0.785

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TABLE 18. (continued)

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m^3)	Total Inflow Volume (m^3)	Runoff Volume at time of cutoff (m^3)
6	1	1	52.3	224.5	292.5	15.0	3.731	3.755	50.252	65.908	0.744
		3		144.5	228.5	19.0	2.654	2.669	23.012	36.596	1.208
		5		171.5	229.5	10.5	2.960	2.947	30.456	40.583	0.430
	2	1	59.5	131.5	214.5	25.5	3.095	3.219	24.417	41.424	1.962
		3		131.0	218.5	19.0	2.827	2.922	22.219	38.310	2.242
		5		171.0	223.0	14.0	3.791	3.849	38.894	51.504	0.434
7	1	1	25.3	184.0	233.5	22.0	3.052	3.213	33.690	45.010	0.588
		3		66.0	99.0	32.0	2.851	2.961	11.289	17.591	0.747
		5		46.0	99.0	28.0	3.774	3.921	10.415	23.288	3.159
	2	1	27.8	98.0	145.0	21.5	2.808	2.885	16.514	25.102	0.963
		3		113.0	145.0	25.0	2.966	2.946	20.109	25.629	--
		5		90.0	139.5	29.0	3.542	3.700	19.126	30.971	--
8	1	1	16.9	90.5	117.5	27.0	3.541	3.557	19.227	25.078	0.205
		3		57.5	119.0	37.5	2.494	2.523	8.605	18.017	2.551
		5		90.5	120.0	33.0	2.359	2.374	12.808	17.090	0.325
	2	1	20.9	134.0	172.5	29.5	2.380	2.415	19.136	24.994	0.366
		3		111.0	171.0	33.0	2.771	2.808	18.457	28.807	1.416
		5		120.5	173.0	35.0	3.398	3.430	24.565	35.603	1.022

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TABLE 19. DATA SUMMARY FOR THE BENSON FARM (1977).

Irrigation Number	Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (mm)	Total Recession Time (mm)	Average Inflow Rate During Advance (lps)	Average Inflow Rate (lps)	Inflow Volume During Advance (m^3)	Total Inflow Volume (m^3)	Runoff Volume at time of cutoff (m^3)
1	1	1	40.0	81.0	670.0	44.0	1.206	1.026	5.862	41.265	9.354
2	1	1	44.0	95.7	714.0	43.6	1.592	1.489	9.142	63.786	23.292
		3		121.9	714.0	40.4	1.421	1.424	10.396	61.006	15.271
		5		91.7	714.0	43.8	1.644	1.617	9.046	69.283	29.407
3	1	1	67.0	243.5	698.0	48.0	1.617	1.610	23.623	67.428	18.792
		3		344.0	698.0	45.7	1.338	1.326	27.612	55.549	10.423
		5		252.0	698.0	48.5	1.336	1.392	20.197	58.277	20.072
4	1	1	87.0	199.0	705.0	53.0	0.896	0.783	10.698	33.101	8.723
		3		221.2	705.0	45.0	1.068	1.050	14.179	44.429	4.543
		5		162.0	705.0	47.3	1.050	1.133	10.209	47.917	12.293

TABLE 20. DATA SUMMARY FOR THE HORTICULTURE, NCRDC, AND STIEBEN FARMS.

Farm	Irrigation Number	Field or Group Number	Furrow Number	Soil Moisture Deficit (mm)	Total Advance Time (min)	Total Inflow Time (min)	Total Recession Time (min)
Horticulture	1	1	1	100.0	61.5	202.0	20.0
			3		47.7	202.0	19.5
			5		67.5	202.0	17.5
NCRDC	2	1	1	72.0	32.0	300.0	19.2
			3		38.6	300.0	18.5
			5		33.0	300.0	19.2
	2	2	1	50.0	33.2	300.0	17.0
			3		31.5	300.0	15.0
			5		25.0	300.0	15.0
Stieben	3	1	1	70.0	200.0	450.0	26.0
			3		180.0	450.0	30.0
			5		182.0	450.0	27.0
	4	1	1	95.0	94.0	696.0	35.0
			3		88.0	696.0	35.5
			5		76.0	696.0	31.0

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APPENDIX B

PROCEDURES USED FOR THE EVALUATION OF FURROW IRRIGATION PERFORMANCE
(from Neff, 1981)

B.1 INTRODUCTION

Each of the procedures are detailed in a step-by-step fashion. Procedures 1 to 3 are alternate procedures to Procedure 4 which is the most detailed procedure. In cases where a step may be the same as a step in a preceding procedure, the step is labeled "same as Procedure X, Step 9B."

B.2 Procedure 1 (simplest procedure)

Step 1. Preliminary Field Survey.

A. Gather Soil Survey Information

Soil types and basic intake rate

B. Farmer Interview

Field history, irrigation practices and problem areas

C. On-site Inspection

Step 2. Select, Measure and Mark Furrows to be Evaluated.

A. Select for Representative Evaluation

B. Chain and Stake Furrows as follows:

Stake 1 -- Near head ditch but out of turn row.
Stake 2 -- Five meters down furrow from Stake 1.
Stake 3 -- Midpoint between first and last stake.
Stake 4 -- Near physical end of furrow but far enough upfield to avoid flooding and turn row.

Step 3. Day Prior to Irrigation Evaluate Soil Moisture Deficit (SMD)

A. Use "feel method"

B. Record estimate of percent of total available water (TAW) depleted to nearest 25 percent

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C. For soils near field capacity assume 10 percent depletion of TAW

D. Apply percent depletion to total available water obtained from soil survey information to get SMD

Step 4. During Irrigation Record Irrigation and Advance Times.

A. Start time -- time for water to reach Stake 1.

B. Advance time to middle and end (Stakes 3 and 4).

C. Time of cutoff -- time of furrow flow is stopped at Stake 1 by using dirt, shovel or sheet metal to block flow.

Step 5. Estimate Furrow Inflow.

A. Count number of furrows set and divide into total flow, or

B. Measure or estimate head on tube and tube size to obtain inflow

C. Measure size of gated pipe opening and pipe pressure

Step 6. Measure Depth and Top Width.

A. At Stake 2 only

B. A minimum of 3 times during irrigation period

Step 7. Following Irrigation, Compute Average Surface Storage Area

A. Compute area from A = 2/3TD where T is average top width and D is average depth of flow

B. Multiply result of Step A by 0.77 (surface storage factor)

Step 8. Compute Performance.

A. Use basin intake rate information to estimate c,

B. Compute a and b by solution of two simultaneous equations for volume balance at the middle and end of field

C. Compute infiltrated, runoff and deep percolated volumes (assume 1/2 of surface storage volume infiltrates, the remainder runs off).

D. Compute application efficiency, tailwater ratio and deep percolation ratio

B.3 Procedure 2

Step 1. Same as Procedure 1, Step 1.

Step 2. Same as Procedure 2, Step 2.

Step 3. Day Prior to Irrigation, Determine Soil Moisture.

- A. Probe not earlier than 1 day prior for irrigation or more than one day following irrigation for sandy soils, 2-3 days following for heavier soils
- B. Probe at points 1/4 to 1/3 of the furrow length from Stake 1 and Stake 4
- C. Probe through anticipated root zone at maturity
- D. Combine samples from wet guard furrow, crop row and dry furrow (for alternate furrow irrigation)
- E. Use gravimetric method to determine moisture content

Step 4. Install appropriately sized and calibrated flume at Stake 1.

Step 5. Take profilometer reading at Stake 2.

Step 6. During Irrigation, Record Irrigation and Advance Times.

Same as Step 4 Procedure 1.

Step 7. Record flow depth at Stake 2 several times during irrigation.

Step 8. Periodically record inflow flume depths.

Step 9. Following Irrigation, Remove and Clean Flumes.

Step 10. Determine soil moisture same as Step 3.

Step 11. Take profilometer readings as in Step 5.

Step 12. Compute the soil moisture deficit.

- A. Use book values for bulk density
- B. Convert all gravimetric moisture values to volumetric and find total moisture in root zone
- C. Subtract total pre-moisture from total post-moisture to obtain SMD at each sample point

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D. Average the two values obtained for the furrow or group of furrows being evaluated

Step 13. Compute average surface storage area.

A. Plot profilometer data on graph paper

B. Use graphical method to determine areas for depths of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 cm

C. Fit depth-area information both before and after irrigation to a power-curve fit

D. Obtain cross-sectional area using average depth of flow

E. Multiply by 0.77

Step 14. Compute performance.

A. Calculate a and b using estimate of c value

B. Compute time to infiltrate deficit to check for over or under irrigation

C. Compute infiltrated volumes, runoff volumes and volumes of deep percolation

D. Compute application efficiency, tailwater ratio and deep percolation ratio

B.4 Procedure 3

Step 1. Same as Procedure 1, Step 1.

Step 2. Same as Procedure 1, Step 2.

Step 3. Day Prior to Irrigation, Evaluate SMD

Same as Procedure 1, Step 3

Step 4. Install inflow and outflow flumes.

Step 5. During Irrigation, record irrigation and advance times. In addition to those procedures listed in Procedure 1, Step 4, record the time of completion of recession.

Step 6. Measure depth and top width at Stake 2.

Step 7. Periodically record inflow and outflow flume depths.

Step 8. Following Irrigation, Remove and Clean Flumes.

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Step 9. Compute average surface storage area.

Same as Procedure 1, Step 7

Step 10. Compute inflow and outflow volumes.

A. Use graphical or numerical analysis of hydrograph, or

B. Product of average flow rate and total time of flow

C. Assume outflow decreases linearly at time of cutoff

Step 11. Compute performance.

A. Compute a, b and c using Christiansen Technique and inflow minus outflow at the time of cutoff (described in Section 3.3)

B. Compute time to infiltrate deficit to check for over or under irrigation

C. Compute infiltrated, runoff, and deep percolation volumes

D. Compute efficiencies

Same as Procedure 1, Step 8D

B.5 Procedure 4 -- Detailed Furrow Evaluation Procedure

Step 1. Same as Procedure 1, Step 1.

Step 2. Select, Measure and Mark Furrows to be Evaluated.

A. Select for representative evaluation

B. Stake furrows as follows:

Stake 1 -- near head ditch but out of turn row
Stake 2 -- five meters from Stake 1
Stake at midpoint of field
Last stake set near end of furrow
Chain and stake at 25 meter intervals from Stake 1

Step 3. Survey Furrow Slope.

Step 4. Obtain Soil Bulk Density Samples.

A. Sample through profile

B. Sample in same general location of soil moisture samples

Step 5. Day Prior to Irrigation, Evaluate Soil Moisture.

Same procedure as Procedure 2, Step 3 except sample in at least three locations

Step 6. Install inflow and outflow flumes.

Step 7. Take profilometer readings.

   A. Take reading at Stake 2

   B. Take readings at 50 to 75 meter intervals down field

Step 8. During Irrigation, Record Irrigation and Advance Times. Same as Procedure 3, Step 5

Step 9. Measure depth of flow at Stake 2 several times during irrigation.

Step 10. Periodically record inflow and outflow flume flow depths.

Step 11. Following Irrigation, Remove and Clean Flumes.

Step 12. Evaluate soil moisture (as in Step 5).

Step 13. Compute average surface storage area.

   A. Determine flow areas for flow depths at 0.5 cm intervals over the observed range of depths

   B. Compute power-law relation for area and depth using both pre- and post-irrigation values

   C. Assume a Manning's n of 0.02, the average depth at Stake 2 as normal depth and a surface storage factor of 0.77 and compute average surface storage area

Step 14. Calculate the soil moisture deficit (as in Procedure 2, Step 12, except use measured values of bulk density).

Step 15. Compute inflow-outflow volumes from hydrographs (same as Procedure 3, Step 10).

Step 16. Compute performance (same as Procedure 3, Step 11).

APPENDIX C

ANALYSIS OF HOURLY AND EQUIPMENT REQUIREMENTS AND COSTS
(from Neff, 1981)

C.1 INTRODUCTION

Costs of evaluating each procedure both in terms of labor (hourly costs) and equipment are included in this appendix. Each procedure has an associated "fixed" hourly cost and a variable hourly cost. The fixed costs are costs that occur only once in an annual evaluation of an irrigated field but may vary with the level of evaluation. Variable costs vary not only with the level of evaluation but with the number of irrigations measured. An hourly requirement labeled as "per furrow or group" means the requirement is not increased unless more than one group is evaluated. A group is noted as being two to three furrows not exceeding three per group.

Equipment requirements were estimated based on requirements for equipment used in the 1979 evaluation of all three sites. A large miscellaneous is included to handle lost items, replacement of expendable items and repair costs. Expensive equipment was costed on an annual basis with no cost recovery factor included. Wide variations in costs may occur for changes made in quality of equipment as well as availability, shipping and inflation factors.

C.2 Hourly Requirements for Evaluation Procedures

C.2A Evaluation Procedure 1

Step 1.	8 hours (one time for each field)
Step 2.	3.0 hours/furrow or group*
Step 3.	2.0 hours/furrow or group
Step 4. Step 5. Step 6.	12 hours/furrow or group
Step 7. Step 8.	2 hours/furrow
Misc.	8 hours/furrow or group

* NOTE: A group may be 2 or 3 furrows.

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No. of furrows	Hours/Irrigation	Cost ($7/hr)
1	27	$189.00
2	29	203.00
3	31	217.00
4 (2 groups)	58	406.00
6 (2 groups)	62	434.00

C.2B Procedure 2

Step 1. 8 hours (one time for each field)

Step 2. 3.0 hours/furrow or group*

Step 3. 6 hours/furrow or group

Step 4. 0.25 hours/furrow

Step 5. 0.5 hours/furrow

Step 6.
Step 7. 16 hours/furrow or group
Step 8.

Step 9. 0.25 hours/furrow

Step 10. 6.0 hours/furrow or group

Step 11. 0.5 hours/furrow

Step 12. 2.0 hours/furrow

Step 13. 2.0 hours/furrow

Step 14. 2.0 hours/furrow

Misc. 8.0 hours/furrow or group

No. of furrows	Hours/Irrigation	Cost ($7/hr)
1	46.5	$325.50
2	54.0	378.00
3	61.5	430.50
4	108.0	756.00
6	123.0	861.00

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C.2C Procedure 3

Step 1. 8 hours (one time for each field)

Step 2. 3.0 hours/furrow or group*

Step 3. 2.0 hours/furrow or group

Step 4. 0.5 hours/furrow

Step 5.
Step 6. 20 hours/furrow or group
Step 7.

Step 8. 0.5 hours/furrow

Step 9. 0.5 hours/furrow

Step 10. 4 hours/furrow

Step 11. 2 hours/furrow

Misc. 10.0 hours/furrow or group

No. of furrows	Hours/Irrigation	Cost ($7/hr)
1	42.5	$297.50
2	50.0	350.00
3	57.5	402.50
4 (2 groups)	100.0	700.00
6 (2 groups)	115.0	805.00

C.2D Procedure 4

Step 1. 8 hours

Step 2. 4 hours/furrow

(one time for each field)

Step 3. 2 hours/furrow

Step 4. 8 hours/furrow or group

Step 5. 6 hours/furrow or group*
0.5 hours/furrow

Step 6. 3.0 hours/furrow or group

Step 7.
Step 8. 20 hours/furrow or group
Step 9.

Step 10. 0.5 hours/furrow

Step 11. 6 hours/furrow or group

Step 12. 3.0 hours/furrow or group

Step 13. 8 hours/furrow Computer use -- 2 hours/furrow prep time

Step 14. 2 hours/furrow

Step 15. 4 hours/furrow

Step 16. 2 hours/furrow

Misc. 12 hours/furrow or group

No. of furrows	Hours/Irrigation	Cost ($7/hr)
1	67.0	$ 469.00
2	84.0	588.00
3	101.0	707.00
4	168.0	1,176.00
6	202.0	1,414.00

C.3 Equipment Requirements and Costs for Evaluation Procedures

C.3A Procedure 1

Quantity		Annual Cost
1	Oakfield probe	$ 17.00
2	Metric tapes (3m)	10.00
1	100 ft steel tape	35.00
2	shovels	40.00
2	depth gauges	2.00
1	level	8.00
1	Programmable calculator (HP 33E or TI58C or equivalent)	24.00
1	lantern	10.00
1	bdl stakes (1" x 2" x 16" surveyors)	8.00
1	bdl lathes for tall crops	6.00

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Quantity		Annual Cost	
1	clipboards	3.00	
	Data forms - engineering paper (500 sheets)	25.00	
	Miscellaneous	50.00	1st furrow $25 succeed
		$238.00	

Equipment costs for:

1 furrow	$238.00
2 furrows	263.00
3 furrows	288.00
4 furrows (2 groups of 2)	313.00
6 furrows	363.00

C.3B Procedure 2

Quantity		Annual Cost
1	Oakfield probe	$ 17.00
2	Metric tapes (3m)	10.00
1	100 ft steel tape	35.00
2	shovels	40.00
2	depth gauges	2.00
1	level	8.00
1	sledge hammer	15.00
1	flume/furrow	17.00/furrow
30	soil cans	10.00
1	oven	100.00
1	balance	175.00
1	profilometer	16.67
1	programmable calculator	24.00
1	lantern	10.00
1	bdl stakes	8.00
1	bdl lathes	6.00

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	Quantity	Annual Cost	
2	clipboards	3.00	
	Data forms - engineering paper	50.00	
	Miscellaneous	50.00	1st furrow $25 succeed
		$596.67	

Equipment costs for:

1 furrow	$596.67
2 furrows	638.67
3 furrows	680.67
4 furrows	722.67
6 furrows	806.67

C.3C Procedure 3

	Quantity	Annual Cost	
1	Oakfield probe	$ 17.00	
2	Metric tapes (3m)	10.00	
1	100 ft steel tape	35.00	
2	shovels	40.00	
2	depth gauges	2.00	
1	level	8.00	
1	sledge hammer	15.00	
2	flumes/furrow	34.00	
1	programmable calculator	24.00	
1	lantern	10.00	
1	bdl stakes	8.00	
1	bdl lathes	6.00	
2	clipboards	3.00	
	Data forms	50.00	
	Miscellaneous	75.00	1st furrow $50 succeed
		$337.00	

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Equipment costs for:

1 furrow	$337.00
2 furrows	421.00
3 furrows	505.00
4 furrows	589.00
6 furrows	757.00

C.3D Procedure 4

Quantity		Annual Cost	
1	Oakfield probe	$ 17.00	
2	Metric tapes (3m)	10.00	
1	100 ft steel tapes	35.00	
2	shovels	40.00	
2	depth gauges	2.00	
1	level	8.00	
1	sledge hammer	15.00	
2	flumes/furrow	34.00	
60	soil cans	20.00	
1	oven	100.00	
1	balance	175.00	
1	profilometer	16.67	
1	bulk density probe	30.00	
1	surveyors transit & rod on tripod	25.00	
1	programmable calculator	24.00	
1	lantern	10.00	
2	bdl of stakes	16.00	
2	bdl of lathes	12.00	
2	clipboards (hardboard)	3.00	
	Data forms -- engineering paper	50.00	
	Miscellaneous	100.00	1st furrow $75 succeed
	Spray paint		
	Pencils	$742.67	
	Markers		
	Pennant flags		
	Lantern batteries		
	Calculator batteries		
	Equipment repair and Shovel handles		

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Equipment costs for:

1 furrow	$ 742.67
2 furrows	866.00
3 furrows	975.00
4 furrows	1,084.00
6 furrows	1,302.00

C.4 Summary of Evaluation Costs

Total Cost of Evaluation for:

Procedure 1	Fixed Hourly	Variable Hourly	Equip. Costs	Total
1 furrow	56.00	189.00	238.00	483.00
2 furrows	56.00	203.00	263.00	522.00
3 furrows	56.00	217.00	288.00	561.00
4 furrows	56.00	406.00	313.00	775.00
6 furrows	56.00	434.00	363.00	853.00
2 irrigations	56.00	868.00	363.00	1,287.00
3 irrigations	56.00	1,302.00	363.00	1,721.00
4 irrigations	56.00	1,736.00	363.00	2,155.00
5 irrigations	56.00	2,170.00	363.00	2,589.00

Procedure 2	Fixed Hourly	Variable Hourly	Equip. Costs	Total
1 furrow	56.00	325.00	596.67	978.00
2 furrows	56.00	378.00	638.67	1,073.00
3 furrows	56.00	430.00	680.67	1,167.00
4 furrows	56.00	756.00	722.67	1,535.00
6 furrows	56.00	861.00	806.67	1,724.00
2 irrigations	56.00	1,722.00	807.00	2,585.00
3 irrigations	56.00	2,583.00	807.00	3,446.00
4 irrigations	56.00	3,444.00	807.00	4,307.00
5 irrigations	56.00	4.305.00	807.00	5,168.00

Procedure 3	Fixed Hourly	Variable Hourly	Equip. Costs	Total
1 furrow	56.00	297.50	337.00	691.00
2 furrows	56.00	350.00	421.00	827.00
3 furrows	56.00	402.50	505.00	964.00
4 furrows	56.00	700.00	589.00	1,345.00
6 furrows	56.00	805.00	757.00	1,618.00
2 irrigations	56.00	1,610.00	757.00	2,423.00
3 irrigations	56.00	2,415.00	757.00	3.228.00
4 irrigations	56.00	3,220.00	757.00	4,033.00
5 irrigations	56.00	4,025.00	757.00	4,838.00

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Procedure 4	Fixed Hourly	Variable Hourly	Equip. Costs	Total
1 furrow	154.99	469.00	742.67	1,366.00
2 furrows	196.00	588.00	866.00	1,650.00
3 furrows	238.00	707.00	975.00	1,920.00
4 furrows	336.00	1,176.00	1,084.00	2,596.00
6 furrows	420.00	1,414.00	1,302.00	3,136.00
2 irrigations	420.00	2,828.00	1,302.00	4,550.00
3 irrigations	420.00	4,242.00	1,302.00	5,964.00
4 irrigations	420.00	5,656.00	1,302.00	7,378.00
5 irrigations	420.00	7,070.00	1,302.00	8,792.00

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APPENDIX D

COMPUTER LISTING OF PROGRAM FURSIM
(from Binder, 1981)

```
      PROGRAM FURSIM
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C... PROGRAM FURSIM IS AN EMPIRICAL SIMULATION MODEL FOR
C    PREDICTING FURROW IRRIGATION SYSTEM PERFORMANCE AS A
C    FUNCTION OF THE FOLLOWING DECISION VARIABLES:  FURROW
C    DISCHARGE (Q), TIME OF CUT-OFF (TCO), SOIL MOISTURE
C    DEFICIENCY (SMD), AND NUMBER OF PREVIOUS IRRIGATIONS
C
C
C... THIS VERSION OF PROGRAM FURSIM IS IN THE PRODUCTION MODE
C
C
C************************  LIST OF SYMBOLS  ****************************
C
C
C... A=AAA=AAV=COEFFICIENT IN MODIFIED KOSTIAKOV EQUATION
C... ANCOM=CONSTANT IN MODIFIED MANNINGS EQUATION
C... ARCOF1,ARCOF2=COEFFICIENTS IN ARCOM-FUNCTION
C... ARCOM=CONSTANT IN RELATIONSHIP FOR FLOW AREA AS A
C           FUNCTION OF FLOW DEPTH
C... AWPCOM=CONSTANT IN RELATIONSHIP FOR WETTED PERIMETER
C           AS A FUNCTION OF FLOW DEPTH
C... B=BBB=BAV=ETNF=COEFFICIENT IN MODIEFFIED KOSTIAKOV EQUATION
C... BNCOM=EXPONENT IN MODIFIED MANNINGS EQUATION
C... BRCOM=EXPONENT IN RELATIONSHIP FOR FLOW AREA AS A
C           FUNCTION OF FLOW DEPTH
C... BWPCOM=EXPONENT IN RELATIONSHIP FOR WETTED PERIMETER
C           AS A FUNCTION OF FLOW DEPTH
C... C=CCC=CAV=COEFFICIENT IN MODIFIED KOSTIAKOV EQUATION
C... CCOF1,CCOF2=COEFFICIENTS IN C-FUNCTION
C... CDA=CHRISTIANSEN TECHNIQUE Y-INTERCEPT
C... CMA=CMAA=CMADUM=AVERAGE AREA OF SURFACE STORAGE DURING ADVANCE
C... CMM=AVERAGE AREA OF SURFACE STORAGE AT TIME OF CUT-OFF
C... C1,C2,C3,C4,C5=DUMMY VARIABLES
C... DA=VOLUME INFILTRATED AS USED IN CHRISTIANSEN TECHNIQUE
C... DUMINO=IRRIGATION NUMBER
C... EA=EEA=APPLICATION EFFICIENCY
C... ER=ERR=REQUIREMENT EFFICIENCY
C... F=FRACTION OF SURFACE STORAGE THAT INFILTRATES AFTER
C       TIME OF CUTOFF
C... FARM=FARM NAME
C... FCOF1,FCOF2=COEFFICIENTS IN F-FUNCTION
C... FF=KIEFER CORRECTION FACTOR
C... I,J,K,L=ARRAY ARGUMENT
C... IRRNO=IRRIGATION IDENTIFICATION
C... MNCOM=MANNINGS N
C... MNCOF1,MNCOF2=COEFFICIENTS IN MNCOM-FUNCTION
C... NPR=COUNTER
C... NSMD=COUNTER
C... NTCO=COUNTER
C... NITER=COUNTER
C... NUMIRR=NUMBER OF IRRIGATIONS TO BE SIMULATED
C... P=PDUM=CAD=CONSTANT IN THE ADVANCE FUNCTION
C... PCOF1,2,3,4,5,6=COEFFICIENTS IN THE P-FUNCTION
C... Q=QQQQ=QDEE=QDUM=QMNT=SIMULATED FURROW DISCHARGE
C... QIMAX=QIMAXC=FURROW DISCHARGE LIMITS DURING SIMULATION
```

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```
C...  QMIN=QMINC=FURROW DISCHARGE LIMITS DURING SIMULATION
C...  QDEL=QDELC=FURROW DISCHARGE INCREMENT DURING SIMULATION
C...  RAV=RRR=EAD=EXPONENT IN THE ADVANCE FUNCTION
C...  RCOF1,2,3,4,5,6=COEFFICIENTS IN THE R-FUNCTION
C...  RDP=RRDP=DEEP PERCOLATION RATIO
C...  RT=RRT=RUNOFF RATIO
C...  S=FURROW SLOPE(M/M)
C...  SM=VOLUMETRIC SOIL MOISTURE PERCENTAGE
C...  SMCOF1,SMCOF2=COEFFICIENTS IN THE SM-FUNCTION
C...  SMD=SMDO=SOIL MOISTURE DEFICIT
C...  SMDDEL=SMD INCREMENT DURING SIMULATION
C...  SMDMAX,SMDMIN=SMD LIMITS DURING SIMULATION
C...  STCCOM=CONSTANT IN AVERAGE SURFACE STORAGE FUNCTION
C...  STECOM=EXPONENT IN AVERAGE SURFACE STORAGE FUNCTION
C...  TCO=TCOO=TIME OF CUT-OFF
C...  TCODEL=TCO INCREMENT DURING SIMULATION
C...  TCOMAX,TCOMIN=TCO LIMITS DURING SIMULATION
C...  TEND=TDUM=TNF=ADVANCE TIME
C...  TOP=INTAKE OPPORTUNITY TIME
C...  TSMD=TDEE=TIME TO INFILTRATE THE DEFICIT
C...  U=DUMMY VARIABLE
C...  V=DUMMY VARIABLE
C...  VDP=VOLUME OF DEEP PERCOLATION
C...  VIN=VOLUME OF INFLOW
C...  VRO=VOLUME OF RUNOFF
C...  W=FURROW SPACING
C...  WP=WETTED PERIMETER
C...  XLEN=XLINF=FURROW LENGTH
C...  XMIN,XMAX=AXES LIMITS USED IN PLOTTING ROUTINE
C...  XNFF=ADVANCE DISTANCE
C...  XXXD=XXXXD=MAXIMUM DISTANCE ALONG FURROW TO WHERE TOP=TSMD
C...  YMIN,YMAX=AXES LIMITS USED IN PLOTTING ROUTINE
C...  ZNITER=COUNTER
C...  ZSMD=COUNTER
C...  ZTCO=COUNTER
C
C*******************************************************************
C
C
      DIMENSION     DA(3),TCOO(20),SMDO(20),Q(100),CMA(100),P(100),TEND(
     1100),EEA(100),EER(100),RRT(100),RRDP(100),XXXXD(100),QDEE(100),VIN
     2(100),VDP(100),VRO(100),AAV(100),BAV(100),CAV(100),RAV(100),TSMD(1
     300),XNFF(3),TNF(3)
      REAL MNCOM,MNCOF1,MNCOF2
    2 READ(5,505)FARM,XLEN,W,S
  505 FORMAT(A10,F5.1,F5.3,F6.4)
      IF(W.EQ.0.0)GO TO 95
      READ(5,504)FCOF1,FCOF2
  504 FORMAT(2F10.3)
      READ(5,506)MNCOF1,MNCOF2
  506 FORMAT(2F10.4)
      READ(5,507)SMCOF1,SMCOF2
  507 FORMAT(2F10.3)
      READ(5,508)CCOF1,CCOF2
  508 FORMAT(2F10.3)
      READ(5,509)ARCOF1,ARCOF2,BRCOM
  509 FORMAT(3F10.3)
```

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```
      READ(5,510)RCOF1,RCOF2,RCOF3,RCOF4,RCOF5,RCOF6
  510 FORMAT(F10.7,5F10.4)
      READ(5,511)PCOF1,PCOF2,PCOF3,PCOF4,PCOF5,PCOF6
  511 FORMAT(F10.7,5F10.4)
      READ(5,516)QIMAX,QIMIN,QDEL
  516 FORMAT(3F10.4)
      READ(5,517)NUMIRR
  517 FORMAT(I5)
      READ(5,528)TCOMAX,TCOMIN,TCODEL
  528 FORMAT(3F10.4)
      READ(5,529)SMDMAX,SMDMIN,SMDDEL
  529 FORMAT(3F10.4)
C
C... THE DO 90 LOOP DETERMINES I/O AS A FUNCTION OF IRRIGATION NUMBER
C
      DO 90 J=1,NUMIRR
      IRRNO=J
C
C... THE FOLLOWING 9 STATEMENTS SET UP THE LIMITS AND INCREMENT
C    FOR THE TCO, SMD AND Q DO LOOPS
C
      QIMAXC = QIMAX*60.*1000.
      QIMINC = QIMIN*60.*1000.
      QDELC=QDEL*60.*1000.
      ZNITER=(QIMAXC-QIMINC)/QDELC
      NITER=ZNITER+1.5
      ZTCO=(TCOMAX-TCOMIN)/TCODEL
      NTCO=ZTCO+1.5
      ZSMD=(SMDMAX-SMDMIN)/SMDDEL
      NSMD=ZSMD+1.5
      DO 15 I=1,NITER
      Q(I)=0.
      CMA(I)=0.
      P(I)=0.
      TEND(I)=0.
      EEA(I)=0.
      EER(I)=0.
      RRT(I)=0.
      RROP(I)=0.
      XXXXD(I)=0.
      QOEE(I)=0.
      VIN(I)=0.
      VOP(I)=0.
      VRO(I)=0.
      AAV(I)=0.
      BAV(I)=0.
      CAV(I)=0.
      RAV(I)=0.
      TSMD(I)=0.
   15 CONTINUE
      DJMINO=FLOAT(J)
      ARCOM=ARCOF1*(DJMINO**ARCOF2)
      MNCOM=(MNCOF1*DJMINO)+MNCOF2
      F=FCOF1+(FCOF2*DJMINO)
      CALL CWPEWP(ARCOM,BRCOM,AWPCOM,BWPCOM)
      J=5./3.
      V=2./3.
```

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```
      ANCOM = ARCOM**U/AWPCOM**V
      BNCOM = (U*BRCOM)-(V*BWPCOM)
      STECOM = HRCOM/BNCOM
      STCCOM = ARCOM*(AWPCOM**V/(.00465*ARCOM**U))**STECOM
C
C... THE DO 92 LOOP DETERMINES I/O AS A FUNCTION OF TCO
C
      DO 92 L=1,NTCO
      IF(L.EQ.1)GO TO 8
      TCOO(L)=TCOO(L-1)+TCODEL
      GO TO 6
    8 TCOO(1)=TCOMIN
    6 CONTINUE
      TCO=TCOO(L)
C
C... THE DO 93 LOOP DETERMINES I/O AS A FUNCTION OF SMD
C
      DO 93 K=1,NSMD
      IF(K.EQ.1)GO TO 18
      SMOD(K)=SMOD(K-1)+SMODEL
      GO TO 16
   18 SMOD(1)=SMOMIN
   16 CONTINUE
      SMD=SMOD(K)
C
C... THE DO 100 LOOP DETERMINES THE INPUT VARIABLES AND
C     PERFORMANCE PARAMETERS AS A FUNCTION OF Q
C
      DO 100 I=1,NITER
      IF(I.EQ.1)GO TO 20
      Q(I)=Q(I-1)+QDELC
      GO TO 30
   20 Q(1)=QIMINC
   30 CONTINUE
      QQQQ=Q(I)/60000.
      QMNT=Q(I)
      SM=SMCOF1-(SMCOF2*SMD)
      WP=AWPCOM*(((MNCOM*QQQQ)/(0.00465*SQRT(S)*ANCOM))**(1./BNCOM))**BW
     1PCOM
C
C... THE FOLLOWING 7 STATEMENTS SOLVE THE P AND R FUNCTIONS
C     SIMULTANEOUSLY
C
      C1=(QQQQ**RCOF3)* (SM**RCOF4)*(WP**RCOF5)*(MNCOM**RCOF5)*RCOF1
      C2=(QQQQ**PCOF3)* (SM**PCOF4)*(WP**PCOF5)*(MNCOM**PCOF5)*PCOF1
      C3=RCOF2
      C4=PCOF2
      C5=(ALOG(C1)+C3*ALOG(C2))/(1.-(C3*C4))
      RAV(I)=EXP(C5)
      P(I)=C2*(RAV(I)**C4)
      CAD=P(I)
      EAD=RAV(I)
      CAV(I)=(CCOF1*QQQQ)+CCOF2
      C=CAV(I)
      CMADUM= 0.77*STCCOM*(((MNCOM*QQQQ)/SQRT(S))**STECOM)
      CMAA=CMADUM
      CMM=CMADUM*1.169
```

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TYPING GUIDE SHEET
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TOP OF IMAGE AREA
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```
      CMA(I)=CMADUM
C
C... THE FOLLOWING 16 STATEMENTS DETERMINE A AND B USING
C     THE CHRISTIANSEN TECHNIQUE
C
      XLINF=XLEN
      XNFF(1) = XLINF/2.
      XNFF(2) = XLINF
      TNF(1) = (XNFF(1)/CAD) *  * (1./EAD)
      TNF(2) = (XNFF(2)/CAD) *  * (1./EAD)
      DA(1) = QMNT * TNF(1)/XNFF(1) - C * TNF(1)/(1. + EAD) - CMAA* 100.
      DA(2) = QMNT * TNF(2)/XNFF(2) - C * TNF(2)/(1. + EAD) - CMAA* 100.
      IF (DA(1).LE.0.0.OR.DA(2).LE.0.0) DA(1) = .04
      IF (DA(1).LE.0.0.OR.DA(2).LE.0.0) DA(2) = .06
      IF (DA(1).GE.DA(2)) DA(2) = DA(1) .
      NPR=2
      CALL FIT (TNF,DA,NPR,0.0,CDA,ETNF)
      IF(ETNF.LE.0.0)ETNF=0.0
      B = ETNF
      FF= ((B - 1.) - EAD * (B - 1.) + 2.)/(1. + EAD)
      A = CDA * (B + 1.)/FF
      AAV(I)=A
      BAV(I)=B
      AAA=AAV(I)
      BBB=BAV(I)
      CCC=CAV(I)
      RRR=RAV(I)
      QDUM=Q(I)
      PDUM=P(I)
      TDUM=(XLEN/PDUM)**(1./RAV(I))
      TEND(I)=TDUM
      CALL TSMDET(AAA,BBB,CCC,W,SMD,TDEE)
      TSMD(I)=TDEE
      CALL EFFQ(AAA,BBB,CCC,PDUM,RRR,TCO,TDUM,TDEE,QDUM,XLEN,SMD,W,CMM,F
     1,EA,ER,RT,ROP,XXXD)
      EEA(I)=EA
      EER(I)=ER
      RRT(I)=RT
      RROP(I)=ROP
      XXXXD(I)=XXXD
      QDEE(I)=Q(I)/60000.
      VIN(I)=(Q(I)*TCO)/1000000.
      VRO(I)=RRT(I)*VIN(I)
      VDP(I)=RROP(I)*VIN(I)
  100 CONTINUE
C
C... THE FOLLOWING STATEMENTS (THROUGH 200-CONTINUE) WRITE OUT
C     THE INPUT VARIABLES AND PERFORMANCE PARAMETERS IN TABULAR FORM
C
      WRITE(6,614)
  614 FORMAT(1H1,//,50X,"FURROW IRRIGATION SIMULATION")
      WRITE(6,615)FARM,IRRNO,TCO,SMD
  615 FORMAT(/,2X,"FARM:",A10,10X,"IRRIG. NO.:",1X,I5,10X,"TCO(MIN):",F7
     1.1,10X,"SMD(MM):",F5.1)
      WRITE(6,619)
      WRITE(6,617)
  617 FORMAT(     //,3X,"Q",8X,"A",7X,"B",6X,"C",7X,"P",6X,"R",4X,"TSMD",
```

BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
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EPA-287 (Cin.)
(4-76)

```
     13X,"TEND",4X,"CMA",5X,"EA",5X,"ER",6X,"VIN",4X,"RRD",5X,"VRO",5X,"
     2ROP",5X,"VDP",6X,"XD")
      WRITE(5,618)
  618 FORMAT(    1X,"(LPS)",40X,"(MIN)",2X,"(MIN)",2X,"(CM**2)",16X,"(M**
     13)", 9X,"(M**3)",10X,"(M**3)",4X,"(M)")
      WRITE(5,619)
  619 FORMAT( 1X,"-------------------------------------------------------
     1-----------------------------------------------------------------------
     2--------")
      DO 200 I=1,NITER
      WRITE(6,620)QDEE(I),AAV(I),BAV(I),CAV(I),P(I),RAV(I),TSMD(I),TEND(
     1I),CMA(I),EFA(I),EER(I),VIN(I),RRT(I),VRD(I),RROP(I),VDP(I),XXXXD(
     2I)
  620 FORMAT(/    ,1X,F5.2,F10.1,F6.3,F8.1,F8.2,F6.3,F7.1,F7.1,F4.2,F7.3,
     1F7.3,F8.1,F7.3,F8.1,F8.3,F8.1,F9.1)
      IF(I.EQ.27)GO TO 300
      IF(I.EQ.54)GO TO 400
      GO TO 200
  300 WRITE(5,616)
  616 FORMAT(1H1,//,47X,"FURROW IRRIGATION SIMULATION (CONT)")
      WRITE(5,615)FARM,IRRNO,TCO,SMD
      WRITE(5,619)
      WRITE(6,617)
      WRITE(5,618)
      WRITE(5,619)
      GO TO 200
  400 WRITE(5,616)
      WRITE(6,615)FARM,IRRNO,TCO,SMD
      WRITE(6,619)
      WRITE(6,617)
      WRITE(6,618)
      WRITE(6,619)
  200 CONTINUE
   93 CONTINUE
   92 CONTINUE
   90 CONTINUE
      GO TO 2
   95 CONTINUE
      END
```

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

```
      SUBROUTINE TSMDET(A,B,C,W,SMD,TSMD)
      REAL ID,ISMD
C
C... THIS SUBROUTINE DETERMINES THE TIME REQUIRED TO INFILTRATE
C     THE SOIL MOISTURE DEFICIENCY (TSMD)
C
      ISMD=SMD*(.1)*W*(100.)*(100.)
      IF(C.GT.0.0)GO TO 10
      X=ALOG(ISMD)-ALOG(A)
      Y=X/B
      TSMD=EXP(Y)
      GO TO 40
   10 TD=ISMD/C
   20 TD=TD-1.
      IF(TD.LE.0.0)TSMD=0.0
      IF(TD.LE.0.0)GO TO 40
      ID=(A*(TD**B))+(C*TD)
      IF(ID.LT.ISMD)GO TO 30
      GO TO 20
   30 TSMD=TD
   40 CONTINUE
      RETURN
      END
```

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BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

```
      SUBROUTINE FIT (X,Y,NPR,CCOF,ACOF,BCOF)
C
C...THIS SUBROUTINE FITS POINTS TO A POWER CURVE-Y=ACOF*X**BCOF- AND CALCULATES
C    CORRELATION COEFFICIENT-R**2
C
C
C
C... THIS SUBROUTINE IS COURTESY OF LEY(1978)
C
      DIMENSION X(100),Y(100),XLN(100),YLN(100)
      SLNX = 0.0
      SLNY = 0.0
      SSLNX = 0.0
      SSLNY = 0.0
      SLNXY = 0.0
      DO 100 I = 1,NPR
          IF (X(I).EQ.0.0) GO TO 100
          IF (Y(I).EQ.0.0) GO TO 100
          XLN(I) = ALOG(X(I))
          YLN(I) = ALOG(Y(I))
          SLNX = SLNX + XLN(I)
          SLNY = SLNY + YLN(I)
          SSLNX = SSLNX + XLN(I) *  * 2
          SSLNY = SSLNY + YLN(I) *  * 2
          SLNXY = SLNXY + YLN(I) * XLN(I)
  100 CONTINUE
      N = NPR
      DO 120 I = 1,N
          IF (X(I).EQ.0.0) GO TO 110
          IF (Y(I).EQ.0.0) GO TO 110
          GO TO 120
  110     NPR = NPR - 1
  120 CONTINUE
      XNPR = FLOAT(NPR)
      BEXP = (SLNXY - SLNX * SLNY/XNPR)/(SSLNX - SLNX *  * 2/XNPR)
      BCOF = BEXP
      ACOF = EXP(SLNY/XNPR - BEXP * SLNX/XNPR)
      RTOP = (SLNXY - SLNX * SLNY/XNPR) *  * 2
      RBOT1 = SSLNX - SLNX *  * 2/XNPR
      RBOT2 = SSLNY - SLNY *  * 2/XNPR
      R2 = RTOP/(RBOT1 * RBOT2)
      RETURN
      END
```

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BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
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EPA-287 (Cin.)
(4-76)

```
      SUBROUTINE CWPEWP (AR,BR,CWP,EWP)
C
C...THIS SUBROUTINE DETERMINES THE RELATIONSHIP OF DEPTH(YWP) WITH WETTED PERIME
C..TER (WP) FOR ANY GIVEN DEPTH OF FLOW AS (WP=CWP*YWP**EWP)--THE PARABOLIC
C     CROSS SECTION IS GIVEN AS AREA  =AR*Y**BR, AND Y IS THE DEPTH OF FLOW(CM)
C
C
C
C... THIS SUBROUTINE IS COURTESY OF LEY(1978)
C
      DIMENSION  YPAR(20),XPAR(20),WWP(20),XPDLT(20),YPDLT(20),DWP(20),W
     1P(20),YWP(20),TW(20),Y(20)
      CXP = AR * BR/2.
      CEXP = (BR - 1.)
      YPAR(1) = 0.0
      WWP(1) = 0.0
      XPAR(1) = 0.0
      DELY = 0.5
      DO 100 IWP = 2,8
         YPAR(IWP) = DELY * FLOAT(IWP - 1)
         XPAR(IWP) = CXP * YPAR(IWP) *  * CEXP
         XPDLT(IWP) = XPAR(IWP) - XPAR(IWP - 1)
         YPDLT(IWP) = YPAR(IWP) - YPAR(IWP - 1)
         DWP(IWP) = SQRT(XPDLT(IWP) *  * 2. + YPDLT(IWP) *  * 2.)
         WWP(IWP) = WWP(IWP - 1) + DWP(IWP)
         WP(IWP - 1) = 2. * WWP(IWP)
         YWP(IWP - 1) = YPAR(IWP)
  100 CONTINUE
      NPR=7
      CALL FIT (YWP,WP,NPR,0.0,CWP,EWP)
      CTW = AR * BR
      ETW = BR - 1.
      RETURN
      END
```

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BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

EPA-287 (Cin.)
(4-76)

```
      SUBROUTINE EFFQ(A,B,C,P,R,TCO,TEND,TSMD,QDUM,XLEN,SMD,W,CMM,F,EA,E
     1R,RT,RDP,XXXD)
C
C... THIS SUBROUTINE DETERMINES THE SIMULATED SYSTEM PERFORMANCE
C      PARAMETERS USING THE INCOMPLETE INTEGRATION TECHNIQUE
C
      REAL IXXXL,IXXXD,IXLEN
      IXXXL = QDUM*TCO
      A1=SMD*(.1)*W*XLEN*(10000.)
      IF(TSMD.GT.TCO)GO TO 10
      XXXD=((TCO-TSMD)/((1./P)**(1./R)))**R
      TXD=TCO-TSMD
      TRAT1=TXD/TCO
      IXXXD=XXXD*A*(TCO**B)*(1.-((R*B*TRAT1)/(R+1.))+((R*B*(B-1.)*(TRAT1
     1**2))/(2.*(R+2.))))+XXXD*C*(TCO-((R*TXD)/(R+1.)))
      IXXXD=IXXXD+(CMM*100.*XXXD*F)
      GO TO 15
   10 CONTINUE
      XXXD=0.
      IXXXD=0.
   15 CONTINUE
      TRAT2=TEND/TCO
      IXLEN=XLEN*A*(TCO**B)*(1.-((R*B*TRAT2)/(R+1.))+((R*B*(B-1.)*(TRAT2
     1**2))/(2.*(R+2.))))+XLEN*C*(TCO-((R*TEND)/(R+1.)))
      IXLEN=IXLEN+(CMM*100.*XLEN*F)
      TOPL=TCO-TEND
      IF(TOPL.LT.TSMD)GO TO 20
C
C... THE FOLLOWING DETERMINES THE PERFORMANCE PARAMETERS FOR THE
C          COMPLETE AND OVER-IRRIGATION CASES
C
      EA=A1/IXXXL
      ER=1.
      RT=(IXXXL-IXLEN)/IXXXL
      RDP=(IXLEN-A1)/IXXXL
      GO TO 30
   20 CONTINUE
C
C... THE FOLLOWING DETERMINES THE PERFORMANCE PARAMETERS FOR
C          THE UNDER-IRRIGATION CASE
C
      IF(TSMD.GT.TCO)GO TO 25
      A4=SMD*(.1)*W*XXXD*(10000.)
      EA=(IXLEN-IXXXD+A4)/IXXXL
      ER=(IXLEN-IXXXD+A4)/A1
      RT=(IXXXL-IXLEN)/IXXXL
      RDP=(IXXXD-A4)/IXXXL
      GO TO 30
   25 CONTINUE
      EA=IXLEN/IXXXL
      IF(TEND.GT.TCO)EA=1.0
      ER=IXLEN/A1
      RT=(IXXXL-IXLEN)/IXXXL
      IF(TEND.GT.TCO)RT=0.0
      RDP=0.
   30 CONTINUE
      IF(RT.LT.0.0)RDP=RDP+RT

      IF(RT.LT.0.0)RT=0.0
      IF(RDP.LT.0.0)EA=EA+RDP
      IF(RDP.LT.0.0)RDP=0.0
      IF(ER.GT.1.0)ER=1.0
      RETURN
      END
```

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